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Painted Rock Reservoir
1993 Water Surface Area and Storage Capacity Estimate Derived from Landsat Data Classification

Emily S. Bryant, Timothy Pangburn, Robert L. Bolus, Gregory A. Pedrick, Gregory Peacock, Brian G. Tracy, and Joseph B. Evelyn

June 1999

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Abstract: The Painted Rock Reservoir, southwest of Phoenix, Arizona, had a storage capacity of about 2.5 million acre-ft in 1959, when dam closure was made. It was projected that the reservoir would lose about 200,000 acre-ft of its capacity to sedimentation over 50 years. When the flood of record occurred in 1993, however, it was feared that as much as 500,000 acre-ft of capacity had been lost, and an updated capacity estimate was needed. Because a proposed conventional reservoir survey turned out to be prohibitively expensive, it was decided to investigate the use of Landsat Thematic Mapper remotely sensed data, acquired at multiple reservoir levels, to obtain an updated capacity estimate at a more reasonable cost.

Nineteen Landsat Thematic Mapper scenes from 1993 and 1995 were obtained, including reservoir elevations ranging from empty to 5 ft above spillway elevation. Water surface area was determined for each Landsat scene using computer classification of the digital imagery. These surface area values, together with reservoir elevation records for the time of the Landsat data acquisitions and 1985 survey information, were used to generate an updated elevation vs. surface area curve for the reservoir, which in turn was used to compute an updated elevation vs. storage capacity curve. Investigation results indicate that the Painted Rock Reservoir lost approximately 157,000 acre-ft of storage capacity to sedimentation between 1953 and 1993, significantly less than the 500,000 acre-ft previously feared lost.

This technique of using remotely sensed data to update area and capacity curves could be applied to other reservoirs, if (among other conditions) there is a record of reservoir elevation at the time of acquisition of the remotely sensed data, and if cloud-free data are available for the entire range of reservoir elevations from full to empty.

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Prepared for
U.S. ARMY ENGINEER DISTRICT, LOS ANGELES
and for
OFFICE OF THE CHIEF OF ENGINEERS

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PREFACE

This report was prepared by Emily Bryant, Physical Scientist, Remote Sensing/ Geographic Information System Center (RS/GISC), U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire; Timothy Pangburn, Hydraulic Engineer, RS/GISC; Robert L. Bolus, Physical Scientist, RS/GISC; Gregory A. Pedrick, Electrical Engineer, formerly with the Applied Research Division, CRREL; Gregory Peacock, Chief, Water Control Data Unit, U.S. Army Corps of Engineers, Los Angeles District (LAD), Los Angeles, California; Brian G. Tracy, Reservoir Regulation Section Chief, LAD; and Joseph B. Evelyn, Hydraulics and Hydrology Branch Chief, LAD.

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CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	*By*	*To obtain*
acre	4,046.873	$meter^2$
acre-ft	1,233.489	$meter^3$
foot	0.3048	meter
inch	25.4	millimeter
inch	0.0254	meter
mile	1,609.347	meter
$mile^2$	2,589,998.0	$meter^2$

Painted Rock Reservoir
1993 Water Surface Area and Storage Capacity Estimate Derived from Landsat Data Classification

EMILY S. BRYANT, TIMOTHY PANGBURN, ROBERT L. BOLUS, GREGORY A. PEDRICK, GREGORY PEACOCK, BRIAN G. TRACY, AND JOSEPH B. EVELYN

INTRODUCTION

This project was conducted to estimate the current storage capacity and the elevation vs. storage capacity relationship of the Painted Rock Reservoir, Arizona, using an elevation vs. surface area curve determined from Landsat Thematic Mapper (TM) remote sensing data.

The Painted Rock Dam is located on the Gila River at river mile 126, southwest of Phoenix, Arizona (USACE 1962, 1993). Figure 1 gives an overview of the region, showing the reservoir in the south with Phoenix to the northeast in yellow tones. The dam and reservoir are managed by the Los Angeles District of the U.S. Army Corps of Engineers. The dam was constructed between 1957 and 1960 for flood control; closure was made in April 1959. The drainage area above the dam is 50,800 square miles. The reservoir is empty at water surface elevation of 530 ft above mean sea level (MSL), with spillway crest at 661 ft and the top of the dam at 705 ft. The reservoir's water surface elevation for the period 1959 to 1997 is shown in Figure 2.

As of a 1953 aerial survey, the water surface area of the reservoir at spillway elevation was 53,200 acres and the storage capacity at the same elevation was 2,491,700 acre-ft. It was estimated in 1962 that 200,000 acre-ft of sediment would be deposited in the reservoir (no elevation specified) over the course of 50 years. As of a 1985 survey, 15,631 acre-ft had been lost at spillway elevation. In 1993, the flood of record for Painted Rock Reservoir occurred, and a dam upstream was breached as well. This led reservoir managers to project that much more sediment than originally estimated—as much as 500,000 acre-ft—might have been deposited in the reservoir.

With the large influx of sediment from the 1993 flood event, the elevation vs. capacity relationship for the Painted Rock Reservoir needed to be updated for managers to maintain effective water control procedures. The cost of a ground survey was prohibitive, so it was worth investigating the use of remotely sensed data as an alternative information source. Pertinent references for methodologies on calculating the effect of sedimentation on reservoirs are included in U.S. Army Corps of Engineers Engineering and Design manuals EM 1110-2-4000 (USACE 1989) and EM 1110-2-1420 (USACE 1997).

It is known that the reservoir elevation went from full to empty in 1993, and there possibly exists a snapshot of the state of the reservoir every 16 days when the Landsat satellite passed over. Also available is a complete record of water elevation at the dam, so the exact water elevation at the time of Landsat overpasses can be retrieved. It is also known that water and land are spectrally very distinct, making it likely that classification of Landsat data will yield a reasonably accurate water surface area estimate. With this information, it should be possible to generate updated surface area values for the selected elevations of the times of the Landsat overpasses.

The updated surface area values for selected reservoir elevations can be used to update the existing complete surface area curve from the 1985 survey. An updated elevation vs. capacity curve can then be created by computing the area under the updated surface area curve.

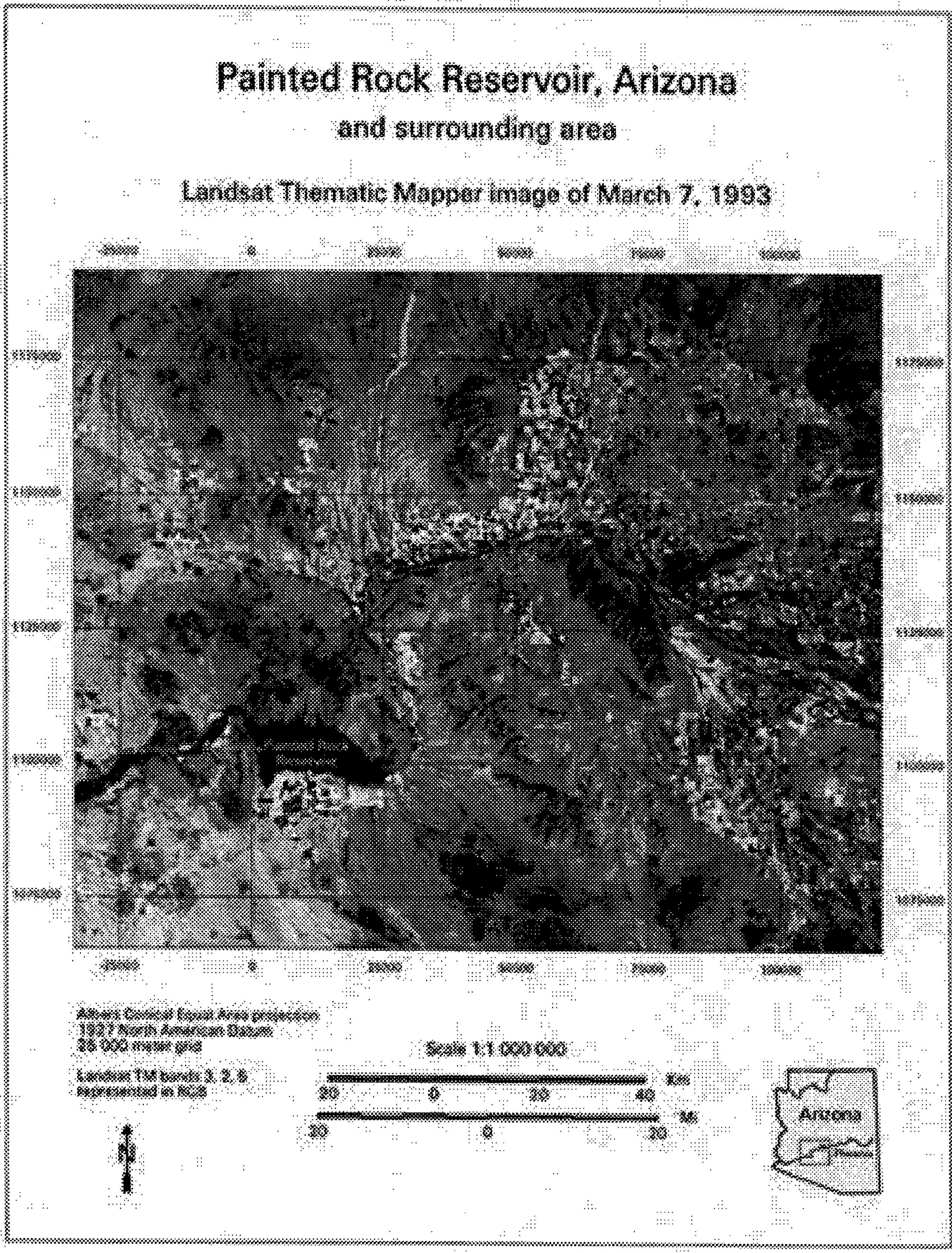

Figure 1. Painted Rock Reservoir, Arizona, and surrounding area.

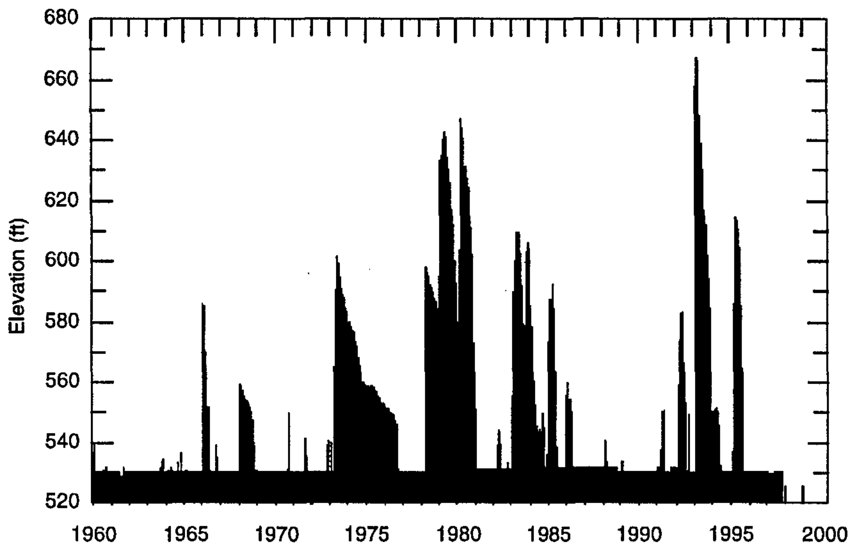

Figure 2. Water surface elevation of Painted Rock Reservoir, 1959–1997. Elevation is in ft above MSL. Flood of record occurred in 1993. (Graphic provided by Gregory Peacock.)

DATA

Landsat TM remotely sensed data, Digital Line Graph (DLG) data from the U.S. Geological Survey, reservoir elevation data from the time of the Landsat overpasses, area and capacity data from previous surveys, and 1993 ground survey profiles were used for this project.

Landsat Thematic Mapper data

The first Landsat satellite was launched in 1972; Landsats 4 and 5 are still operating. They orbit the earth at an altitude of approximately 450 miles, with repeat coverage every 16 days. The TM instrument records the earth's reflected radiation in six spectral bands (Band 1, blue; Band 2, green; Band 3, red; Band 4, near-infrared; and Bands 5 and 7, mid-infrared) and its emitted (thermal) radiation in one band (Band 6). Each Landsat TM scene covers a ground area of about 100 x 100 miles, with a pixel size of approximately one-fifth of an acre (28.5 m x 28.5 m). Additional background information on Landsat is available on the World Wide Web (USGS 1998a).

Nineteen Landsat TM scenes were used for this project (Table 1). All are located at Path 37,

Table 1. Landsat scenes of Painted Rock Reservoir.

Entity ID	*Acquisition date*	*Acquisition time (GMT)*	*Sun elevation (degrees)*	*Sun azimuth (degrees)*	*Weather over reservoir*
LT5037037009306610	7 Mar 93	17:26	40.00	134.00	Clear
LT4037037009309010	31 Mar 93	17:17	47.56	126.02	Clear
LT5037037009309810	8 Apr 93	17:26	51.60	125.79	Clear
LT5037037009311410	24 Apr 93	17:26	56.26	120.01	Clear
LT5037037009313010	10 May 93	17:26	59.64	113.56	Clear
LT5037037009314610	26 May 93	17:26	61.51	107.41	Clear
LT5037037009317810	27 June 93	17:26	61.43	101.81	Clear
LT5037037009321010	29 July 93	17:26	58.47	108.75	Clouds at E. end
LT5037037009324210	30 Aug 93	17:26	53.39	123.74	Clear (1 sm. cloud)
LT5037037009327410	1 Oct 93	17:26	45.62	138.84	Clear
LT5037037009330610	2 Nov 93	17:26	36.35	148.31	Clear
LT5037037009333810	4 Dec 93	17:25	28.87	150.69	Clear
LT5037037009504010	9 Feb 95	17:15	30.84	138.32	Haze
LT5037037009507210	13 Mar 95	17:14	40.58	130.31	Clear
LT5037037009510410	14 Apr 95	17:12	50.93	120.16	Wispy clouds
LT5037037009513610	16 May 95	17:11	57.50	107.56	Wispy clouds
LT5037037009516810	17 June 95	17:10	58.49	98.93	Clear
LT5037037009520010	19 July 95	17:08	55.97	101.40	Many puffy clouds
LT5037037009523210	20 Aug 95	17:07	51.64	113.35	Clouds SE

Row 37 of the Landsat World Reference System #2. The data, which were acquired from March through December 1993 and from February through August 1995, were purchased from the USGS's EROS Data Center through the National Imagery and Mapping Agency (NIMA). (See USGS [1998a] and NIMA [1998] for further information.) The 1993 scenes were generally clear; 1995 scenes had problems with clouds, and were not used in the final area and capacity estimates.

Digital Line Graph data

DLG data at 1:100,000 scale were downloaded from the U.S. Geological Survey's Global Land Information System (USGS 1998a) for use in rectifying the Landsat data. These are vector data, and include hydrography, roads, railroads, and miscellaneous transportation layers, digitized from 1:100,000-scale paper maps or from photographs. For each layer, the 1:100,000-scale quadrangle map area is broken into eight 15-minute by 15-minute sections. Quadrangle names and sections of downloaded data are listed in Table 2.

Table 2. Downloaded DLG data.

1:100,000-scale quadrangle name	*File name prefix*	*Sections downloaded*
Bradshaw Mountains, Arizona	PK4	1–8
Salome, Arizona	PH1	3, 4, 7, 8
Little Horn Mountains, Arizona	PH3	3, 4, 7, 8
Phoenix North, Arizona	PH2	1–8
Phoenix South, Arizona	PH4	1–8
Gila Bend, Arizona	AJ2	1–8
Theodore Roosevelt Lake, Arizona	ME1	1–8
Mesa, Arizona	ME3	1–8
Casa Grande, Arizona	TS1	1–8
Silver Bell Mountains, Arizona	TS3	1, 2, 5, 6

Horizontal accuracy of the maps from which these data are derived is listed as 0.02 inches at the scale of the map (approximately 50 m or 167 ft on the ground). The digitization process adds an error that is less than or equal to 0.003 inches (approximately 7.6 m or 25 ft on the ground).

Reservoir elevation data

Reservoir elevations, obtained from Los Angeles District's Reservoir Regulation section, are staff readings made by the dam tender. Table 3 lists the reservoir elevations at the times of the Landsat overpasses.

Table 3. Reservoir elevation at time of Landsat data acquisition.

Acquisition date	*Acquisition time (GMT)*	*Reservoir elevation (ft)*	*Note*
7 Mar 93	17:26	665.86	*
31 Mar 93	17:17	655.24	*
8 Apr 93	17:26	651.68	*
24 Apr 93	17:26	644.22	*
10 May 93	17:26	637.75	*
26 May 93	17:26	631.06	*
27 Jun 93	17:26	620.61	C
29 Jul 93	17:26	612.32	*
30 Aug 93	17:26	604.88	*
1 Oct 93	17:26	594.65	C
2 Nov 93	17:26	578.51	*
4 Dec 93	17:25	532.10	A
9 Feb 95	17:15	531	E
13 Mar 95	17:14	607.35	C
14 Apr 95	17:12	612.80	C
16 May 95	17:11	605.18	*
17 Jun 95	17:10	592.20	C
19 Jul 95	17:08	567.40	*
20 Aug 95	17:07	530.5	E

Notes:
* – (Linearly) Interpolated staff gage reading.
C – Read cfs from chart and adjusted.
A – (*) adjusted by +1.5 ft.
E – Estimated.

Area and capacity data from previous surveys

Elevation vs. surface and elevation vs. capacity information from surveys was available for two dates previous to the 1993 flood: 1953 and 1985. Tables C1 and C2 in Appendix C list these values for every 2 ft of elevation.

According to the reservoir regulation manual, the 1953 data were derived from an aerial survey. No accuracy information was available for these data, but area values are rounded to the nearest 100 acres, which may give an indication of the accuracy.

The 1985 data are from October 1985. The horizontal accuracy for this survey is 1 ft per 5000 ft, and the vertical accuracy is ± 2.5 ft. The effect of this uncertainty on capacity was not indicated.

1993 ground survey profiles

Fifteen profiles across the reservoir were surveyed in 1993 while the reservoir was empty. The profiles consist of 2228 survey points, with easting, northing, and elevation values for each point. These data were supplied by the Los Angeles District as an ARC/INFO coverage. Accuracy figures for the survey were not available.

PROCEDURES

A typical procedure for making remotely sensed data useful for applications consists of three basic steps:

1. Rectify the data spatially, i.e., orient the pixel rows and columns to a known geographic coordinate system such as latitude/longitude, Universal Transverse Mercator (UTM), or Albers, and specify pixel size.
2. Classify the data. Each pixel is assigned to a surface cover-type based on its spectral characteristics. For instance, those pixels that are dark in the visible portion of the spectrum and bright in the near-infrared would be assigned to a vegetation surface type, while those dark in both visible and near-infrared would be assigned to water.
3. Verify accuracy. Compare classification results with reference information (ground truth) for verification.

The Landsat data were processed on a Sun SparcStation 20 UNIX workstation. Software used was ERDAS IMAGINE version 8.3, and Research Systems' ENVI, version 2.6.

In this project, surface area was determined by classifying the Landsat data; storage capacity was computed from the surface area values; sediment depth estimates were derived from the updated area and capacity values; sources of error in the area and capacity estimates were identified and quantified; and an estimate was made of what the elevation vs. area and elevation vs. storage capacity curves would have looked like if 500,000 acre-ft of storage capacity had been lost.

Although the goal of the project is to estimate the capacity of the reservoir, it is noted that the Landsat data contribute only area estimates to this process, and only for selected reservoir elevations. Different approaches can be taken to derive the complete area and capacity curves from the Landsat area estimates.

Surface area procedure

The procedure to estimate the surface area of the reservoir was to select the Landsat scenes, rectify each one to the Albers conical equal area projection and subset the image, classify for water, mask the classification results by hand, and tally acreage. A multitemporal water classification map was created from the individual classification maps, and was compared with the ground survey profile points for verification.

Landsat scene selection

Landsat scenes from both 1993 and 1995 were used for the capacity estimate in the preliminary report (Pangburn et al. 1998), but for this final report, only scenes from 1993 were used, for a number of reasons. The 1993 data give a consistent picture of the reservoir at that time; by 1995 the reservoir could have changed. The 1993 data also had less cloud cover than the 1995 data, and depict a greater range of reservoir elevations. Finally, ground survey profile data available were from 1993, so it is more valid to compare them with Landsat data from 1993 rather than 1995.

Rectification to Albers projection

USGS 1:100,000-scale DLG data were used to rectify the 7 March 1993 Landsat scene. The Albers conical equal area projection was used for the output projection of the rectified image because it is the same as that used in the Los Angeles District's implementation of the CorpsView software. It is an equal area projection, which makes each pixel the same size, thus giving more accurate surface area estimates. Table 4 lists the Albers projection parameters.

Table 4. Albers projection parameters for Painted Rock Reservoir.

Projection	Albers conical equal area
Spheroid	Clarke 1866
Datum	NAD27
Units	meters
Albers projection parameters:	
1st standard parallel	32 36 00 N
2nd standard parallel	38 00 00 N
Central meridian	113 00 00 W
Latitude of projection's origin	23 00 00 N
False easting (meters)	0
False northing (meters)	0

Once the 7 March 1993 scene was rectified, it was used to rectify the remaining scenes. From 28 to 73 ground control points were selected in each scene, using a second-order polynomial warp, with a root-mean-square (rms) error ranging between 15.3 m and 46.7 m. The cubic convolution resampling technique was used; output pixel size was 28.5 m × 28.5 m, which corresponds to 0.2007 acres. Each full scene was rectified, and then a subarea including the reservoir and some area around it was extracted. Table 5 lists the Albers coordinates of the rectified full scene and subset areas. These areas were the same for all 19 Landsat scenes.

Water classification

As mentioned above, water and land are spectrally distinct, making it relatively straightforward to separate water from land with a number of classification techniques. A challenge arises,

Table 5. Albers coordinates of rectified images.

		Upper left corner		*Lower right corner*	*#cols #rows*
Full scene	E	−71563.5 m	E	152,218.5 m	7853
	N	1220712.0 m	N	1,020,015.0 m	7043
Reservoir	E	−23199.0 m	E	46,882.5 m	2460
subarea	N	1127631.0 m	N	1,072,369.5 m	1940

Pixel size = 28.5 m × 28.5 m

however, with pixels that include part land and part water, along the shoreline of the reservoir. It is not appropriate to assign the whole area of any such "mixed" pixel to either water or land; rather, the area should be divided between water and land according to the proportion of land and water in the pixel. There are enough mixed pixels that it is not appropriate to ignore them. The water area classification technique described below (using TM bands 4 and 5), which is referred to as the "Band 5 threshold" technique, was developed to accommodate the mixed pixels. Other techniques might work as well or indeed be more appropriate for other situations, in particular where the water body being looked at was not as well defined, but this technique has the advantage of being relatively simple and has results that are easy to interpret.

In developing this classification technique, a determination of which of the seven Landsat TM spectral bands to use was required. The distinction between water and other surface types varies among the bands, as can be seen in Figure 3, which shows the east end of the reservoir on 7 March 1993. Band 5 (mid-infrared) was selected as the basis for the water classification because water is spectrally uniform and distinct from land. Band 4 (near-infrared) was added to eliminate some confusion between vegetated areas and shoreline areas, which look similar in Band 5 (dark, but not black), but which are distinct in Band 4 (shoreline is dark, vegetation is bright). The visible bands (TM Bands 1, 2, 3) were not used because they had significant spectral variability within the water class, caused by varying amounts of sediment load. TM Band 6 (thermal infrared) was not used because of poor spatial resolution. Band 7 (mid-infrared) was not used,

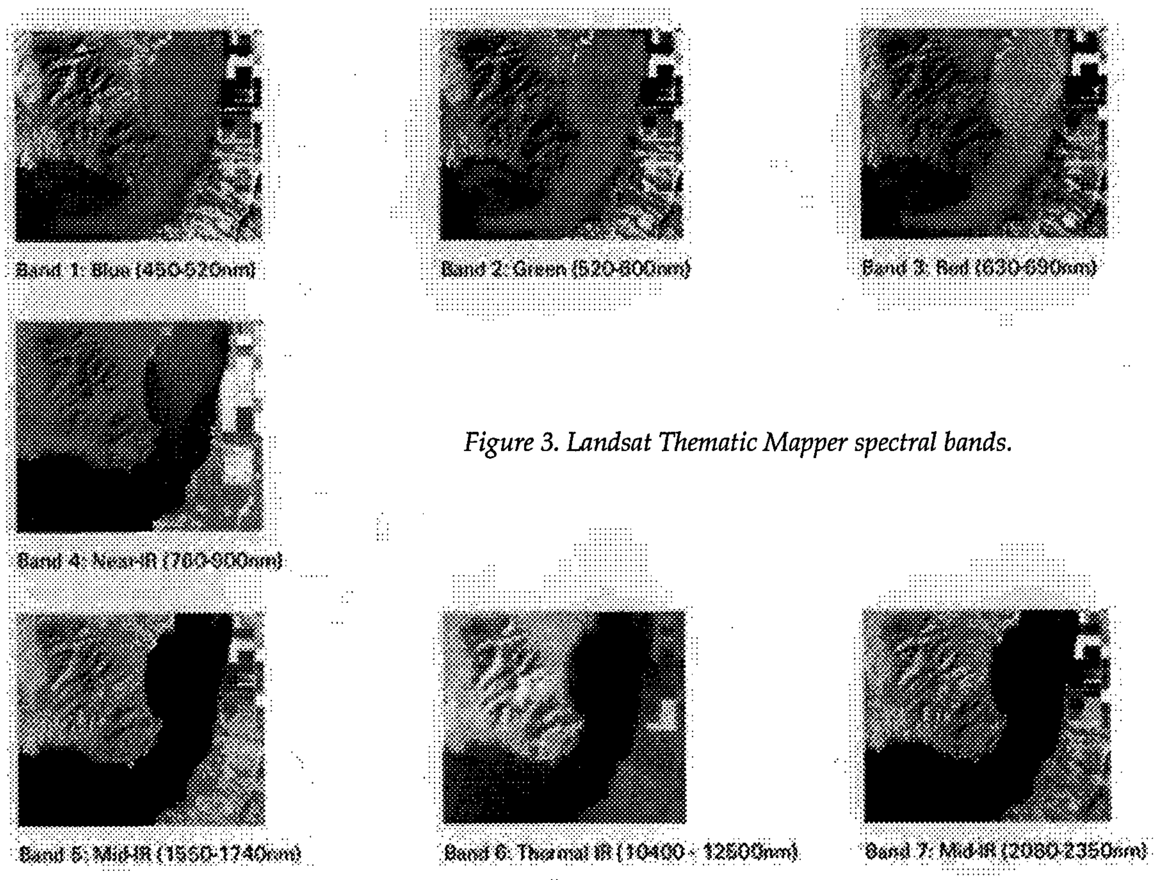

Figure 3. Landsat Thematic Mapper spectral bands.

Table 6. TM Band 5 limits of 21 classes.

Class	TM Band 5 reflectance Min.	Max.	Surface type
1	—	0.0	water
2	0.0	0.01	
3	0.01	0.02	
4	0.02	0.03	
5	0.03	0.04	
6	0.04	0.05	
7	0.05	0.06	
8	0.06	0.07	
9	0.07	0.08	shoreline
10	0.08	0.09	
11	0.09	0.10	
12	0.10	0.11	
13	0.11	0.12	
14	0.12	0.13	
15	0.13	0.14	
16	0.14	0.15	
17	0.15	0.16	
18	0.16	0.17	
19	0.17	0.18	
20	0.18	0.19	
21	0.19	0.20	land

All classes had the additional criterion that TM Band 4 reflectance had to be ≤ 0.2029.

even though it is very similar to Band 5, because it has a smaller data range than Band 5.

Next, the spectral band data used in the classification (Bands 4 and 5) were converted from radiance values (total amount of energy reflected) to reflectance values (percent of incoming energy reflected) using a function available in the ENVI software. This helped compensate for illumination variation through the year. The amount of illumination varies with the sun elevation angle, which ranged from 29° to 62° in the Landsat data used (see Table 1).

The data were then classified. Any pixel with Band 4 reflectance value greater than 0.2029 was eliminated from consideration because it was more likely to be vegetation than shoreline or water. Remaining pixels were classified into one of 21 classes, based on the Band 5 reflectance value. Table 6 lists the classes with their Band 5 minimums and maximums.

The 21 classes were then divided into three surface types: water (low Band 5 reflectance), shoreline (intermediate Band 5 reflectance), and land (high Band 5 reflectance). The exact cutoff thresholds between water, shoreline, and land were selected separately for each scene by visually examining the images. These thresholds are listed in Table 7.

Table 7. Thresholds for water, shoreline, and land classes for each Landsat scene.

Landsat scene	Water classes	Shoreline classes	Land classes
7 Mar 93	1–3	4–10	11–21
31 Mar 93	1–5	6–16	17–21
8 Apr 93	1–5	6–16	17–21
24 Apr 93	1–5	6–16	17–21
10 May 93	1–6	7–16	17–21
26 May 93	1–5	6–18	19–21
27 Jun 27 93	1–6	7–16	17–21
29 Jul 29 93	1–6	7–16	17–21
30 Aug 93	1–5	6–13	14–21
1 Oct 93	1–5	6–16	17–21
2 Nov 93	1–6	7–16	17–21
4 Dec 93	1–6	7–16	17–21

Hand masking

All scenes were masked by hand to eliminate terrain shadows, clouds and cloud shadows, floating debris, stranded pools of water outside the reservoir, and vegetated areas. A line separating the upper end of the reservoir pool from the river was also drawn manually, using the point where the river becomes braided as an indicator of the upstream end of the reservoir pool.

Acreage tally

The pixels remaining in the unmasked areas were tallied and scaled to acres. Total water surface area was then computed by summing 100% of the area of the water pixels and a prorated amount of area from the shoreline pixels. For instance, for the 27 June 1993 Landsat scene, classes 1–6 were tallied as 100% water, and classes 7–16 (10 classes) were prorated: class 7 at 91% water, class 8 at 82% water, and so on, with class 16 at 9% water, and classes 17–21 as 0% water.

Multitemporal water classification map

A multitemporal water classification map was created by combining the individual water classifications of the 11 scenes from 1993 in which the reservoir was not empty. The first class in this multitemporal classification included all pixels classified as water in the scene with the lowest water level (2 November, 578.51 ft elevation). The second class included all pixels classified as water in the scene with the next highest water level (1 October, 594.65 ft), excluding those pixels already assigned to the first class. A similar procedure was used to create the remaining classes, up to the scene with highest water level (7 March 1993, 665.86 ft). This multitemporal classification includes only the 100% water classes from the individual scenes and

Table 8. Elevation range for each multitemporal class.

Multitemporal class	Scene date (1993)	Elevation range represented (ft)
1	2 Nov	< 578.51
2	1 Oct	578.51–594.65
3	30 Aug	594.65–604.88
4	29 Jul	604.88–612.32
5	27 Jun	612.32–620.61
6	26 May	620.61–631.06
7	10 May	631.06–637.75
8	24 Apr	637.75–644.22
9	8 Apr	644.22–651.68
10	31 Mar	651.68–655.24
11	7 Mar	655.24–665.86

does not include the shoreline classes. Each class represents a range of elevation (Table 8).

Verification comparison

To make an assessment of the Landsat classification, the ground survey profile points from 1993 were superimposed on the 1993 multitemporal water classification. Each survey point was located in an image pixel and its class was noted. Then the elevation as measured at each survey point was compared with the elevation range of the class it fell into. If the class is correct, the survey elevation should lie within the elevation range of the class. Profile cross sections were created, showing ground survey elevation and Landsat elevation range.

Storage capacity procedure

A two-step procedure was used to make an updated estimate of the elevation vs. storage capacity curve for the Painted Rock Reservoir. First, the elevation vs. water surface area curve resulting from the 1985 survey was updated using the 11 area estimates derived from the 1993 Landsat data, and then an updated capacity vs. elevation curve was computed from the updated area curve.

Updated elevation vs. surface area curve

Water surface area values from the 1985 survey were available from the Los Angeles District in hard copy for 0.1-ft intervals, from elevation 525 ft to 705 ft; these were transcribed to digital form for 2-ft intervals. By interpolating from the 0.1-ft data, 1985 area values were determined for the same 11 reservoir elevations as the 1993 Landsat passes. The difference between the 1985 and 1993 surface area values was computed for these 11 reservoir elevations. Difference values for the full elevation range, at 2-ft intervals, were then interpolated from the 11 difference values; these differences were then subtracted from the 1985 area vs. elevation curve to create the updated 1993 area vs. elevation curve. Areas for reservoir elevations above 665.86 ft were not computed because there were no Landsat data with higher elevation.

Updated elevation vs. storage capacity curve

The updated elevation vs. storage capacity curve was computed by integrating under the updated elevation vs. area curve. Capacity of each 2-ft elevation interval was computed by multiplying the elevation difference (2 ft) by the average area of the upper and lower elevations for that interval. To compute the total reservoir capacity for each elevation, the capacities of all intervals up to that elevation were summed. Capacity values for elevations above 665.86 ft. were not computed.

Sediment depth estimation procedure

If it is assumed that the volume of sediment deposited between 1985 and 1993 is equal to the reservoir capacity lost in that time period, then the average depth of the sediment deposited can be computed. This is done by dividing the volume lost (acre-ft) by the area over which the loss is distributed (acres), yielding the average depth of sediment (ft). The depth can be computed for different parts of the reservoir as follows.

The range of reservoir elevations can be divided into elevation increments—in this case, according to the elevation of the reservoir at the time of the Landsat overpasses. The first elevation increment is 530 ft (empty) to 578.51 ft, then 578.51 ft to 594.65 ft, 594.65 ft to 604.88 ft, etc., with the last increment being 655.24 ft to 665.86 ft.

As the reservoir elevation increases from a lower level to a higher one, the surface area of the reservoir increases. The area at the higher level includes the same area as that of the lower elevation plus an extra incremental ring of area. Each new higher elevation level adds an incremental ring of area. The area at any elevation can be considered the sum of the area for the lowest level plus the area of each subsequent incremental area ring.

The reservoir capacity (water volume) also increases with increasing reservoir elevation. As elevation increases, the reservoir capacity includes all the capacity of the lower level plus a layer of water volume as thick as the elevation increment. Each higher elevation adds an incremental volume layer. The reservoir capacity at any elevation therefore can be thought of as the sum of the volume of the lowest layer plus the volume of each of the incremental volume layers.

By knowing the volume for each incremental volume layer for each of two years (in this case, 1985 and 1993), it can be determined how much volume was lost per layer over that time period by subtracting the incremental volumes. Part of any one layer lies over water (the next lower water layer), part over land (the incremental area increase ring for that elevation increment). The part of the layer lying over water cannot have lost any volume to sedimentation because the sediment would keep sinking through the water below. This means that the volume lost in this layer has to be assigned to the part of the layer lying over land, which corresponds exactly to the incremental area ring for that elevation increment. The average depth of sediment in that incremental area ring can be determined by dividing the volume lost in an incremental volume layer by the area of the incremental area ring. This procedure was used to compute the average sediment depth for the incremental area rings associated with the 11 1993 Landsat scenes.

Error analysis procedure

A number of assumptions had to be made in this procedure for estimating the volume of the reservoir using Landsat data, and a number of uncertainties exist in the methods used. An attempt was made to identify and quantify the sources of uncertainty. These are not formal error estimates, but should give a feeling for the magnitude of the uncertainty. For each case, a reasonable maximum error was estimated. Because there were no probabilities associated with these error estimates, formal statistics were not possible.

For error sources #1 through #5 below, the procedure used to estimate the error bars for storage capacity was to estimate the error in water surface area, and then recompute the elevation vs. storage capacity curve, as outlined in the Storage capacity procedure section above, using areas plus and minus the estimated error.

Sources of error are described below. Undoubtedly there are other sources of error as well, including those involved in the technique used to compute capacity from area. More detail on the error analysis can be found in Appendix D.

Mudflats (#1)

For some scenes and in certain locations, the intermediate "shoreline" classification category covered rather extensive areas, instead of a one-pixel-wide area. It was uncertain whether these areas were shallow water or mudflats, and how they should be counted in the water surface acreage tally. The error bars were determined by including and excluding these pixels from the area estimate.

Rectification (#2)

There is some uncertainty inherent in the rectification procedure, caused by error in the DLG data and in selection of control points. The error estimate in this case was derived from an estimate of the error in the DLG data, because that error was estimated as larger than the control point error.

Wind setup (#3)

To derive capacity estimates, it was assumed that the reservoir was level. If there is wind at the time of the Landsat overpass, the water surface may not be level, and the area reported for the elevation given at the dam may be higher (west wind) or lower (east wind) than for level water. Error bars were computed making a number of assumptions, but in particular that all scenes had a half-gale-force wind, either east or west.

Classification threshold (#4)

In the Band 5 threshold classification procedure, it was a judgment call as to where to put the dividing line between water and shoreline, and between shoreline and land. These error bars give what the difference in water area would be if the thresholds for all the scenes were moved either up or down one value.

Masking (#5)

It was a judgment call as to where to draw the line between the reservoir pool and the flowing water at the upstream end of the reservoir. The masking error was figured by outlining an alternate "reasonable maximum" and "reasonable minimum" water area that might have been included.

Depth reading (#6)

The reservoir elevation readings at the dam presumably have some uncertainty. To compute the error bars, it was assumed that the elevation readings at the time of the overpasses were all either 0.1 ft high or 0.1 ft low. At the exact elevations of the Landsat passes, the effect on the capacity is much greater (thousands vs. hundreds of acre-ft) and in the opposite direction than at the intermediate elevations.

Lowest levels (#7)

Because the lowest elevation represented in the

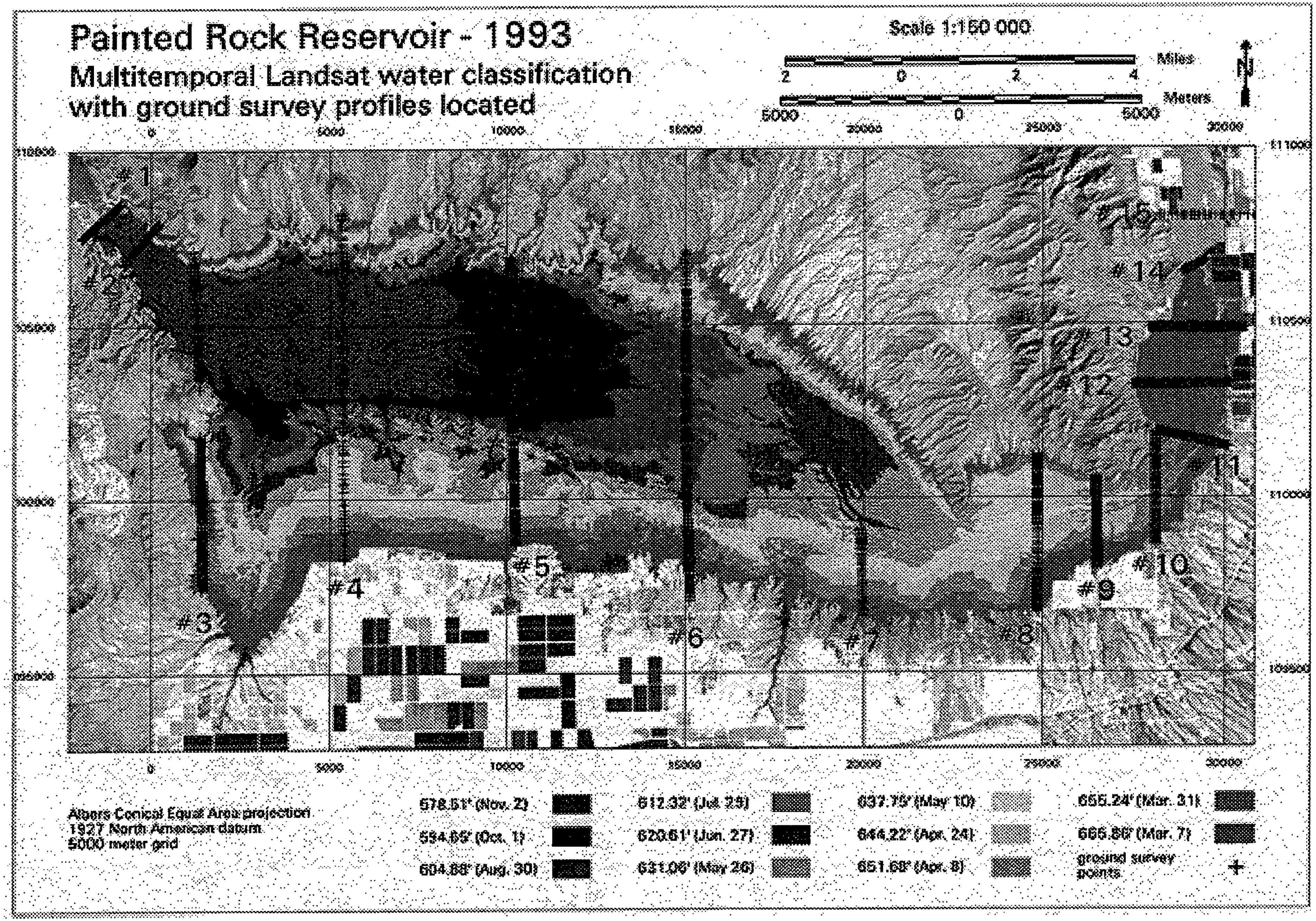

Figure 4. 1993 multitemporal water classification with ground survey profile points overlaid.

1993 satellite data is 48 ft above empty, the area and capacity estimates for these lower elevations are not as reliable as those for higher elevations. In particular, the difference interpolation method yielded negative area estimates for elevations below 546 ft. The underestimate of capacity was estimated to be not more than about 2000 acre-ft. This error, because it is associated with the lowest reservoir level, is carried through to the upper levels as well.

500,000-acre-ft-loss scenario

Reservoir managers initially estimated that 500,000 acre-ft of storage capacity might have been lost after the 1993 flood. The question is whether the loss measured with the Landsat procedure is significantly different from this, given the procedural uncertainties.

In order to make an estimate of area and capacity curves for the 500,000-acre-ft-loss scenario, it is first observed that because the capacity curve is computed as the integral under the area curve, if the area curve is multiplied by a factor, the capacity curve computed from it will be multiplied by the same factor. Given this, a ratio was made of the capacity of the reservoir at spillway elevation if 500,000 acres were lost since 1953 (1,991,700) to the 1993 estimated capacity at spillway elevation (2,334,804). The 1993 area and capacity curves were then multiplied by this ratio at all points to create the new curves. This yielded a capacity curve with the capacity at spillway elevation equal to 1,991,700 acre-ft. This is only one method of modeling these curves, and does not account for different rates of sediment deposition in different parts of the reservoir.

RESULTS

Surface area results

Appendix A presents composite images and classified water surfaces for each of the Landsat scenes. In the classification images, blue represents water, blue–green represents shoreline, and white represents pixels that are either unclassified or masked out. Figure 4 shows the multitemporal water classifications from 1993. Table 9 lists the reservoir water surface area as of 1953 and 1985 (from survey data) and as of 1993 as derived from Landsat data. These values are for the reservoir elevations at the time of the Landsat overpasses. Figure 5 graphs the elevation vs. surface area curves for the 1953 and 1985 surveys, the 1993 Landsat estimate, and the hypothetical 500,000-acre-ft-loss case.

Table 9. Painted Rock Reservoir water surface area in 1953, 1985, and 1993.

Date	Reservoir elevation (ft)	Surface area (acres) 1953 (survey)	1985 (survey)	1993 (Landsat)	Surface area loss (acres) 1953 to 1993	1985 to 1993
4 Dec 93	532.10	112	33	0	112	33
2 Nov 93	578.51	8,571	8,599	7,779	793	821
1 Oct 93	594.65	14,960	15,367	13,328	1,632	2,039
30 Aug 93	604.88	19,840	19,552	17,623	2,217	1,929
29 Jul 93	612.32	23,376	23,332	21,455	1,921	1,877
27 Jun 93	620.61	27,736	27,730	25,888	1,847	1,842
26 May 93	631.06	33,489	33,512	32,303	1,186	1,208
10 May 93	637.75	37,825	37,913	36,485	1,340	1,428
24 Apr 93	644.22	41,732	42,059	40,934	798	1,124
8 Apr 93	651.68	46,792	46,846	45,795	997	1,051
31 Mar 93	655.24	49,106	49,263	48,633	473	630
7 Mar 93	665.86	56,602	56,660	55,141	1,461	1,519
Spillway	661.00	53,200	53,213	52,101	1,099	1,112

Figure 4 shows the location of the 15 ground survey profiles overlaid on the 1993 multitemporal water classification. The matrix in Table 10 summarizes how the elevation as determined from the multitemporal Landsat classification compares with that from the 1993 ground survey profiles. Diagonal elements in this matrix represent agreement between the Landsat classification and the ground survey profile.

Appendix B shows cross sections of the 15 ground survey profiles. The Landsat elevation range is delimited by the dashed lines while the ground survey elevation is represented by an unbroken line. The Landsat data can be viewed as correct if the unbroken line lies between the dashed lines.

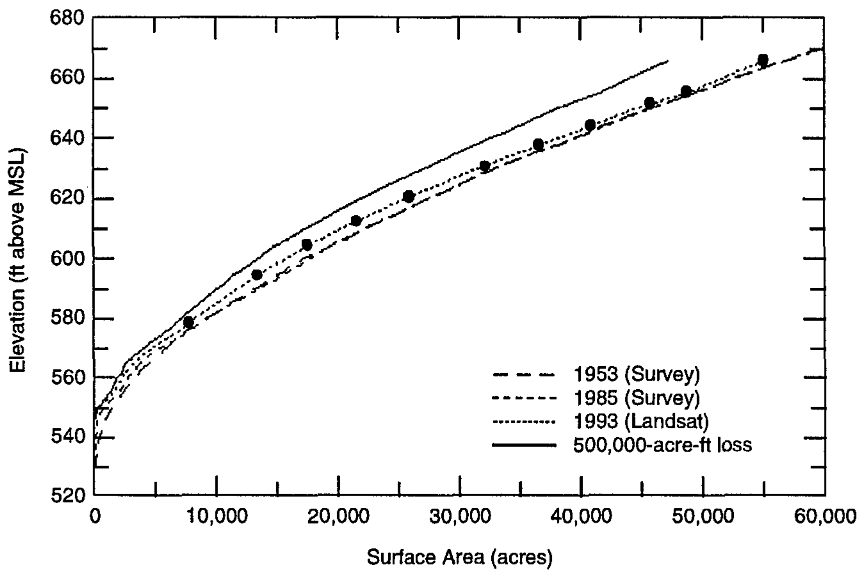

Figure 5. Elevation vs. water surface area graph, with area from 1953 and 1985 surveys, 1993 Landsat estimate, and hypothetical case of 500,00-acre-ft loss of capacity.

Table 10. Painted Rock Reservoir elevation range from Landsat and from 1993 ground survey profiles.

Landsat elevation range	*Ground survey elevation range*												
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*Total*
1	156	14	0	0	0	0	0	0	0	0	0	0	170
2	6	143	4	0	0	0	0	0	0	0	0	0	153
3	1	12	122	40	0	1	0	0	0	0	0	0	176
4	4	4	14	57	16	0	0	0	0	0	0	0	95
5	1	2	2	8	29	8	0	0	0	0	0	0	50
6	0	0	0	0	10	93	20	0	0	0	0	0	123
7	0	0	1	1	4	29	57	25	0	0	0	0	117
8	0	0	1	0	2	3	8	97	8	0	0	0	119
9	0	0	0	0	1	3	4	24	213	15	0	0	260
10	0	0	0	0	0	1	3	0	12	105	58	0	179
11	0	0	0	0	0	0	0	0	1	19	400	37	457
12	0	0	0	0	0	0	0	1	3	1	24	300	329
Total	168	175	144	106	62	138	92	147	237	140	482	337	2,228

Elevation ranges in above table are as follows:

1	empty to 578.51 ft	7	631.06 ft to 637.75 ft
2	578.51 ft to 594.65 ft	8	637.75 ft to 644.22 ft
3	594.65 ft to 604.88 ft	9	644.22 ft to 651.68 ft
4	604.88 ft to 612.32 ft	10	651.68 ft to 655.24 ft
5	612.32 ft to 620.61 ft	11	655.68 ft to 665.68 ft
6	620.61 ft to 631.06 ft	12	665.68 ft and above

Storage capacity results

Storage capacity values from the 1953 and 1985 surveys and the 1993 Landsat estimate are listed in Table 11. Figure 6 graphs the elevation vs. storage capacity curves for the 1953 and 1985 surveys, the 1993 Landsat estimate, and the hypothetical 500,000-acre-ft-loss. The Landsat estimate shows a loss in storage capacity between 1953 and 1993 of about 157,000 acre-ft at spillway elevation (661 ft).

Sediment depth estimate results

Sediment depth estimates are listed in Table 12. Area increment rings correspond approximately to the different classes of the 1993 multitemporal Landsat water classification (Fig. 4).

Table 11. Painted Rock Reservoir storage capacity in 1953, 1985, and 1993.

Date	*Reservoir elevation (ft abv. MSL)*	*Storage capacity loss (acre-ft) 1953 (survey)*	*1985 (survey)*	*1993 (Landsat)*	*Storage capacity (acre-ft) 1953 to 1985*	*1985 to 1993*	*1953 to 1993*
4 Dec 93	532.10	266	34	0	231	34	266
2 Nov 93	578.51	140,816	119,317	99,843	21,498	19,475	40,973
1 Oct. 93	594.65	327,750	311,811	269,280	15,939	42,532	58,470
30 Aug 93	604.88	507,600	490,756	427,929	16,844	62,827	79,671
29 Jul 93	612.32	664,360	650,071	573,090	14,289	76,981	91,270
27 Jun 93	620.61	878,995	861,693	769,297	17,303	92,396	109,698
26 May 93	631.06	1,197,215	1,181,071	1,072,738	16,144	108,333	124,477
10 May 93	637.75	1,434,250	1,419,975	1,302,822	14,276	117,152	131,428
24 Apr 93	644.22	1,691,910	1,678,818	1,553,409	13,092	125,409	138,501
8 Apr 93	651.68	2,029,608	2,010,199	1,876,677	19,409	133,522	152,931
31 Mar 93	655.24	2,202,760	2,181,275	2,044,759	21,485	136,516	158,001
7 Mar 93	665.86	2,755,090	2,743,331	2,595,400	11,759	147,931	159,690
Spillway elev.	661.00	2,491,700	2,476,339	2,334,804	15,261	141,535	156,796

Table 12. Painted Rock Reservoir sediment depth estimate.

Date	*Reservoir elevation increment (ft) Lower bound*	*Upper bound*	*Area of incremental ring (acres)*	*Volume loss in incremental layer (acre-ft)*	*Sediment depth in incremental ring (ft)*
2 Nov 93	empty	578.51	7,779	19,440	2.50
1 Oct 93	578.51	594.65	5,549	23,057	4.16
30 Aug 93	594.65	604.88	4,295	20,296	4.73
29 Jul 93	604.88	612.32	3,832	14,154	3.69
27 Jun 93	612.32	620.61	4,433	15,414	3.48
26 May 93	620.61	631.06	6,415	15,938	2.48
10 May 93	631.06	637.75	4,182	8,819	2.11
24 Apr 93	637.75	644.22	4,449	8,257	1.86
8 Apr 93	644.22	651.68	4,861	8,113	1.67
31 Mar 93	651.68	655.24	2,837	2,994	1.06
7 Mar 93	655.24	665.86	6,508	11,415	1.75

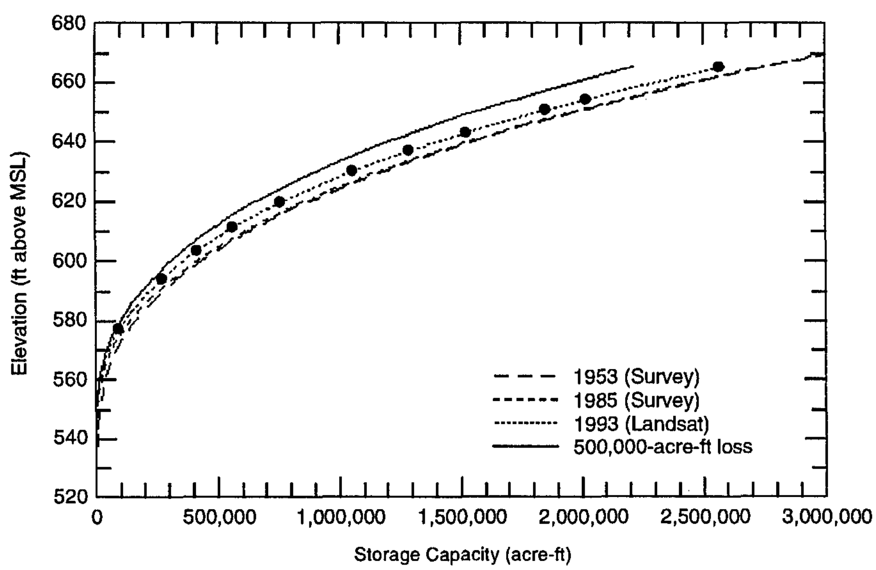

Figure 6. Elevation vs. storage capacity, from 1953 and 1985 surveys, 1993 Landsat estimate, and hypothetical case of 500,00-acre-ft loss of capacity.

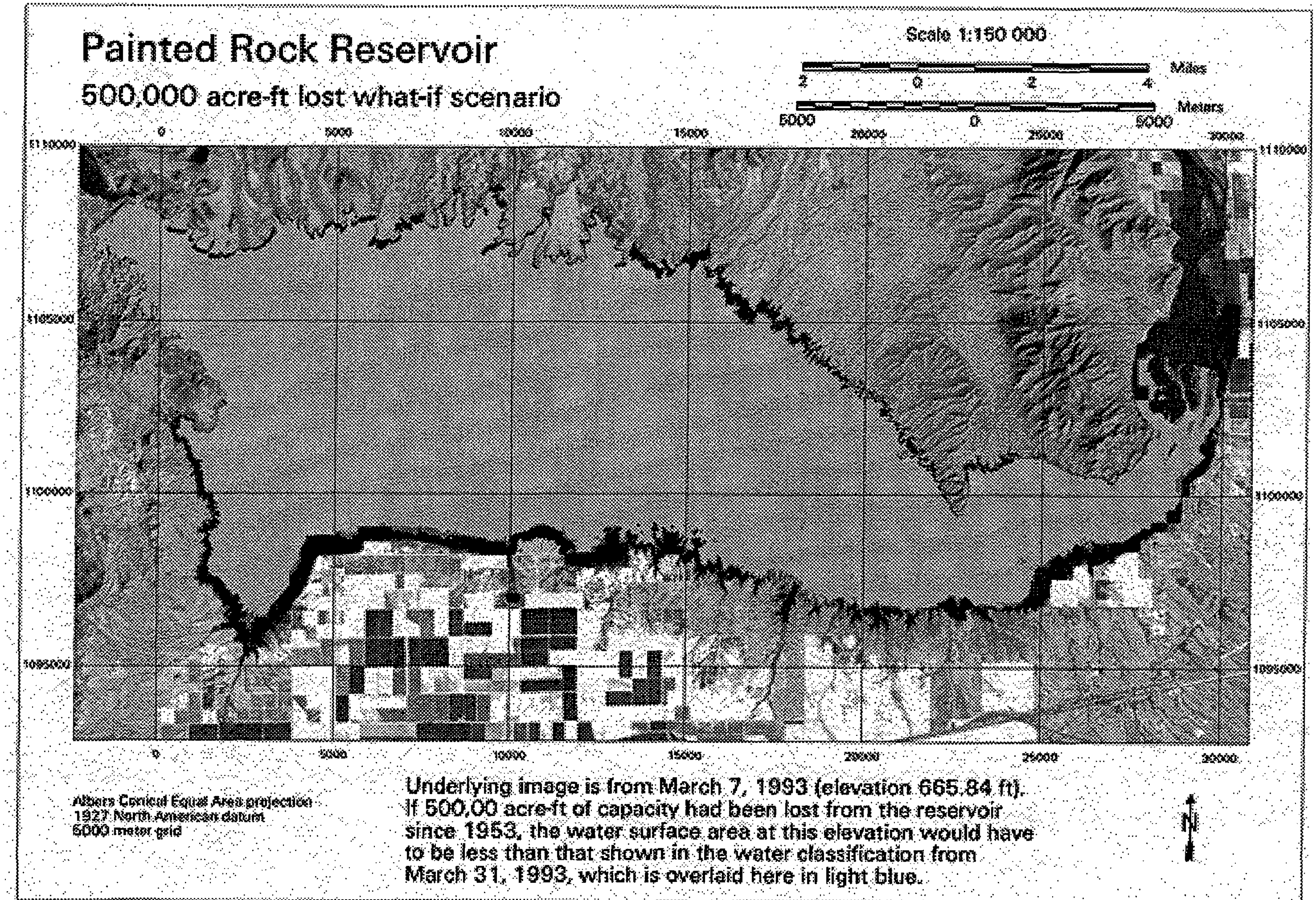

Figure 7. Water classification of 31 March 1993 overlaid on image of 7 March 1993, showing water area if 500,000 acre-ft had been lost.

Table 13. Error bars for Landsat storage capacity estimate at spillway elevation (661 ft).

Error source	*Upper error bar*	*Lower error bar*
#1 Mudflats	40,000	–30,000
#2 Rectification	15,000	–15,000
#3 Wind setup	8,000	–8,000
#4 Threshold	15,000	–16,000
#5 Masking	5,000	–8,000
#6 Depth reading	400	–400
#7 Lowest levels	2,000	0

The area ring for the 594.65- to 604.88-ft elevation range (medium blue color in Fig. 4) has the largest sediment depth estimate (4.73 ft).

Error analysis results

Table 13 lists approximate error bars for the Landsat estimate of storage capacity at spillway elevation. Appendix D explains the error approximations in more detail and gives error estimates for each reservoir elevation level.

500,000-acre-ft-loss scenario results

The estimate of the water surface area and capacity for the elevations of the Landsat overpasses, given a loss of 500,000 acre-ft from 1953 to 1993 (instead of the 157,000-acre-ft loss measured), is listed in Table 14. Estimates for the full range of elevations are given in Tables C1 and C2 in Appendix C.

According to Table 13, if the 500,000-acre-ft-loss scenario were true, then the surface area of the reservoir at elevation 665.86 ft (47,038 acres) would have to be less than the 48,633 acres actually measured with the Landsat data at the next lower elevation, 655.24 ft. This is visualized in Figure 7, which shows the image from 7 March 1993 (elevation 665.86 ft) overlaid with the water surface classification from 31 March 1993 (elevation 655.24 ft). If as much as 500,000 acre-ft had been lost, the 7 March water surface classification would have extended not quite as far as the light blue area in this figure. However, this would clearly leave rather extensive areas of water unclassified, as seen in the dark rim around the edge of reservoir. This rim is larger than just uncertainties in the classification procedure. This leads us to be reasonably sure that not as much as 500,000 acre-ft of storage capacity have been lost.

APPLICABILITY TO OTHER RESERVOIRS

Given that the techniques described in this report prove useful for the Painted Rock Reservoir, the question arises whether it would be possible to use the same techniques to update area and capacity curves for other reservoirs. The following conditions must be met for the techniques to work:

- There must be a record of the water surface elevation of the reservoir at the exact times of the remote sensing data acquisition.
- Remote sensing data must be available for the full range of reservoir elevations, preferably as the reservoir is drawn down rather than as it fills up, because additional sedi-

Table 14. Painted Rock Reservoir surface area and storage capacity estimates for 500,000 acre-ft loss.

Date	*Reservoir elevation (ft above MSL)*	*Measured 1993 area (Landsat) (acres)*	*1993 area if 500,000 acre-ft had been lost since 1953 (acres)*	*1993 capacity if 500,000 acre-ft had been lost since 1953 (acre-ft)*
4 Dec 93	532.10	0	0	0
2 Nov 93	578.51	7,779	6,636	85,171
1 Oct 93	594.65	13,328	11,369	229,709
30 Aug 93	604.88	17,623	15,033	365,044
29 Jul 93	612.32	21,455	18,302	488,873
27 Jun 93	620.61	25,888	22,084	656,247
26 May93	631.06	32,303	27,556	915,097
10 May93	637.75	36,485	31,123	1,111,370
24 Apr 93	644.22	40,934	34,919	1,325,133
8 Apr 93	651.68	45,795	39,066	1,600,896
31 Mar 93	655.24	48,633	41,486	1,744,278
7 Mar 93	665.86	55,141	47,038	2,214,001
Spillway	661.00	52,101	44,444	1,991,700

ment may be deposited after the data are acquired if it is filling up.

- The need for a full suite of data as the reservoir is drawn down requires that the weather be clear a large proportion of the time in the region where the reservoir is located. The Painted Rock Reservoir is optimally situated for this. In areas with more cloud cover than Arizona, it might be worth investigating the use of radar remote sensing data. Radar penetrates clouds, but has other drawbacks.
- The size of the reservoir must be well matched with the resolution of the sensor. A very small reservoir might require a sensor with smaller pixels than the one-fifth-acre pixels of the Landsat TM data. It might also be possible to use data with larger pixels (e.g., Landsat multispectral scanner data, one-acre pixels) for a reservoir as large as or larger than the Painted Rock Reservoir.
- It is definitely desirable, if not required, that the whole reservoir be included in one scene rather than split across multiple scenes, so that the water surface elevation is constant across the reservoir.

CONCLUSION

The technique of classification of Landsat data acquired at various reservoir elevations has yielded updated elevation vs. surface area and elevation vs. storage capacity curves for the Painted Rock Reservoir as of after the 1993 flood. These curves indicate a loss of capacity of about 157,000 acre-ft of storage at spillway capacity since the 1953 survey of the reservoir, and of about 142,000 acre-ft since the 1985 survey. Although there is uncertainty associated with the estimate, it is unlikely that as much as 500,000 acre-ft of capacity have been lost.

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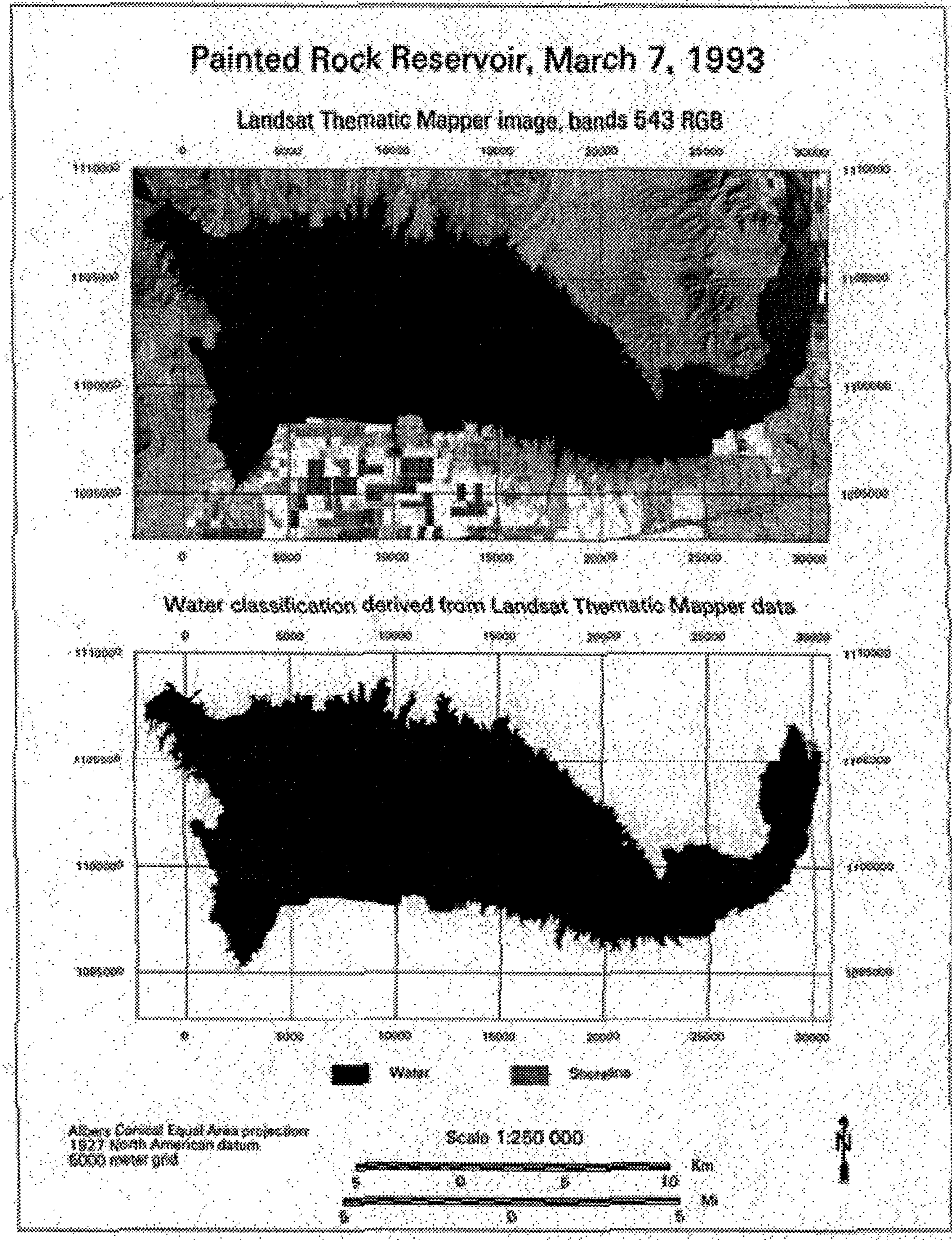
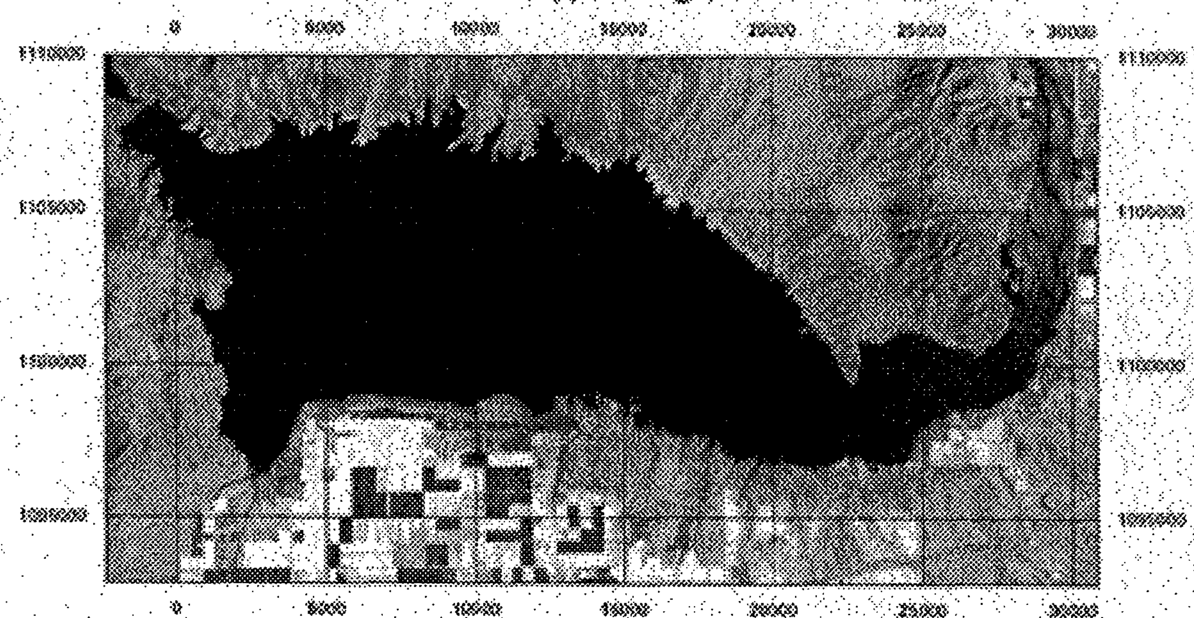
APPENDIX A: COLOR COMPOSITE IMAGES AND WATER CLASSIFICATION

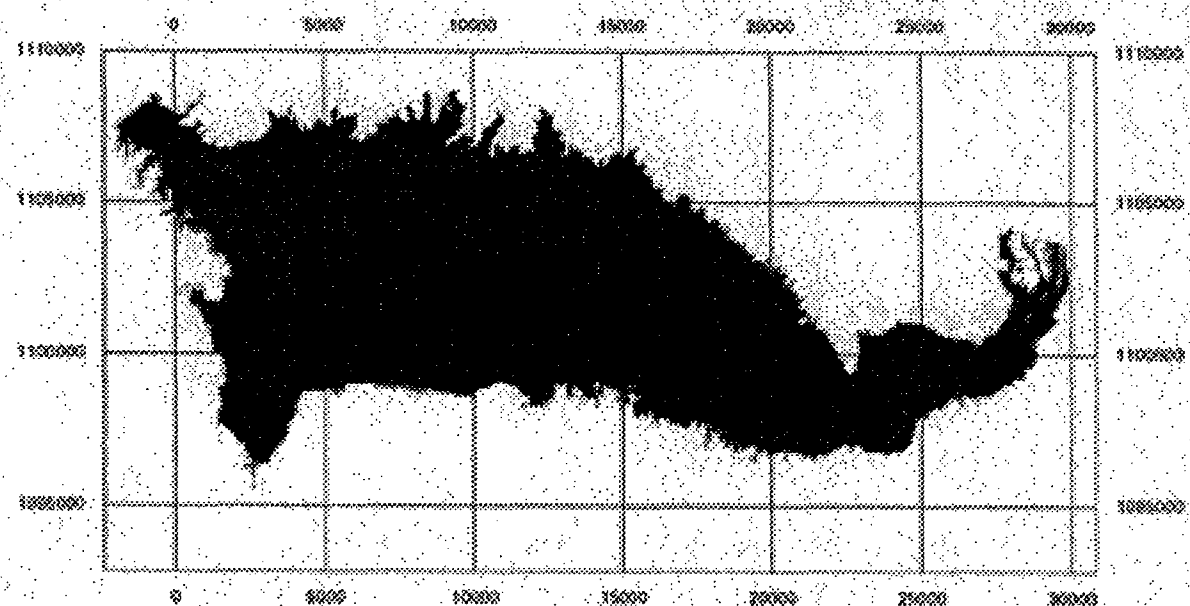

Painted Rock Reservoir, March 7, 1993
Landsat Thematic Mapper image, bands 543 RGB
Water classification derived from Landsat Thematic Mapper data
Water
Albers Conical Equal Area projection
1927 North American datum
Scale 1:250 000
Km
Mi

Painted Rock Reservoir, March 31, 1993

Landsat Thematic Mapper image, bands 543 RGB



Water classification derived from Landsat Thematic Mapper data



Water   Shoreline

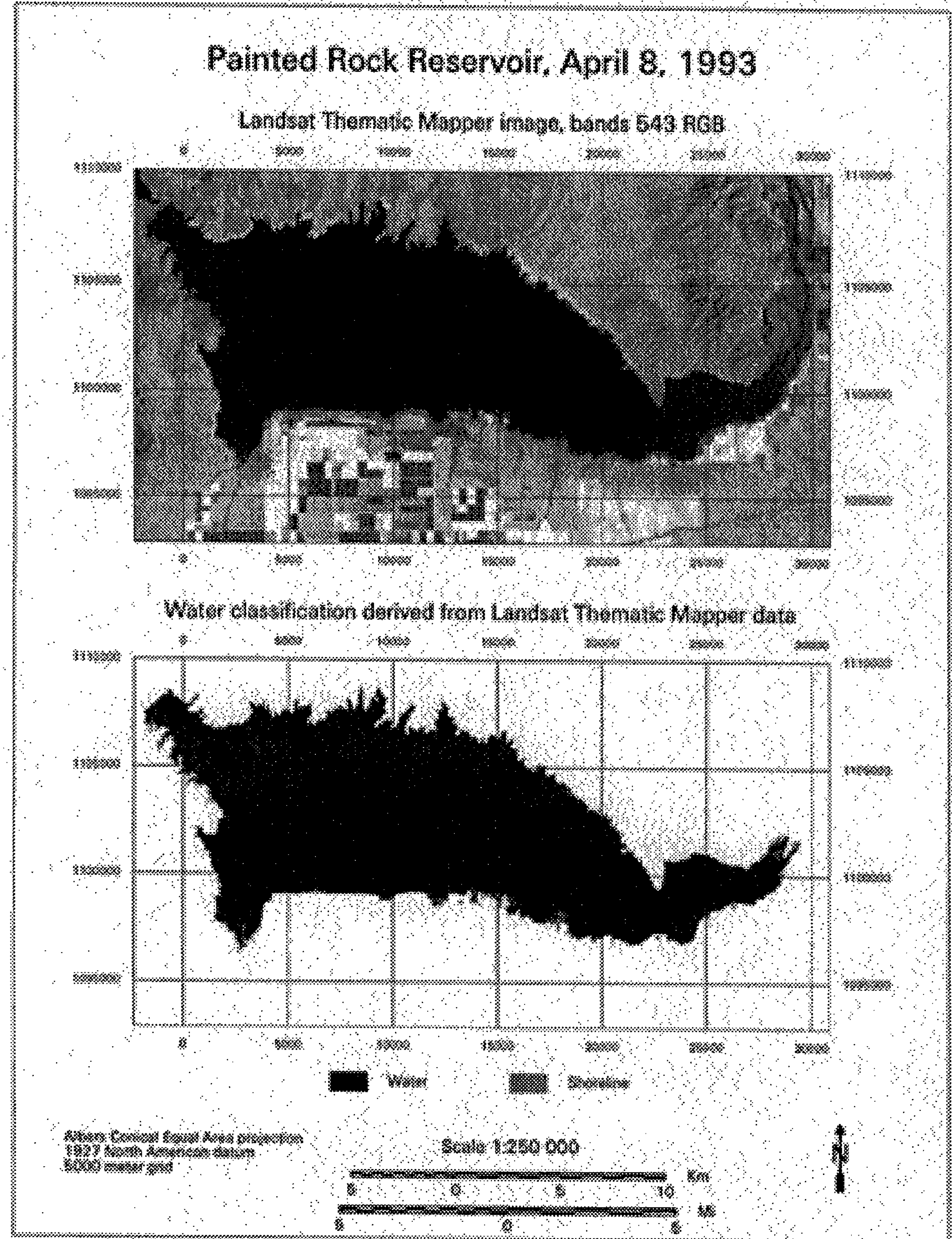
Albers Conical Equal Area projection
1927 North American datum
5000 meter grid

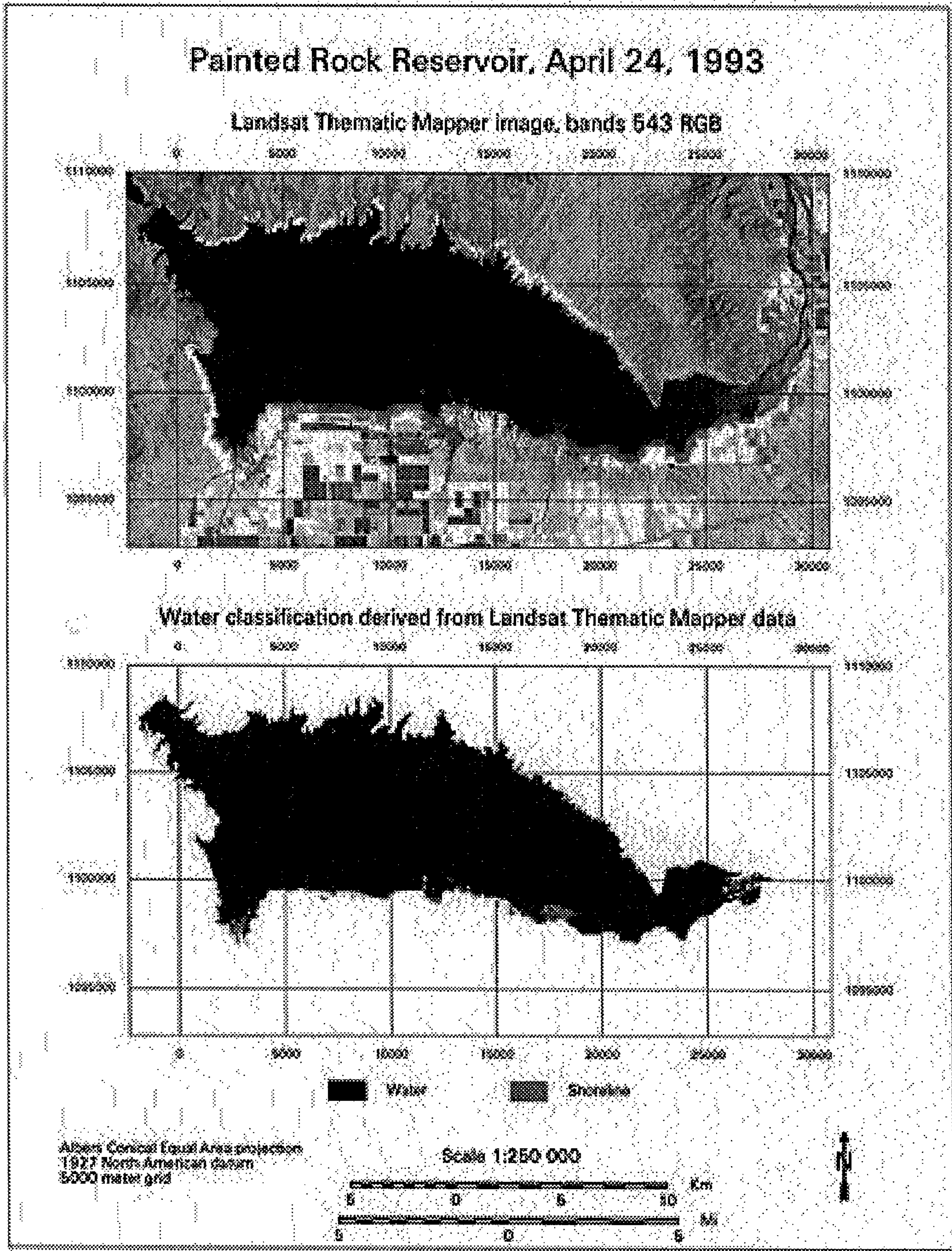
Scale 1:250 000

Km: 5 0 5 10

Mi: 5 0 5

N


Painted Rock Reservoir, April 8, 1993
Landsat Thematic Mapper image, bands 543 RGB
Water classification derived from Landsat Thematic Mapper data
Water
Shoreline
Albers Conical Equal Area projection
1927 North American datum
5000 meter grid
Scale 1:250 000
Km
Mi


Painted Rock Reservoir, April 24, 1993
Landsat Thematic Mapper image, bands 543 RGB
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Shoreline
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5000 meter grid
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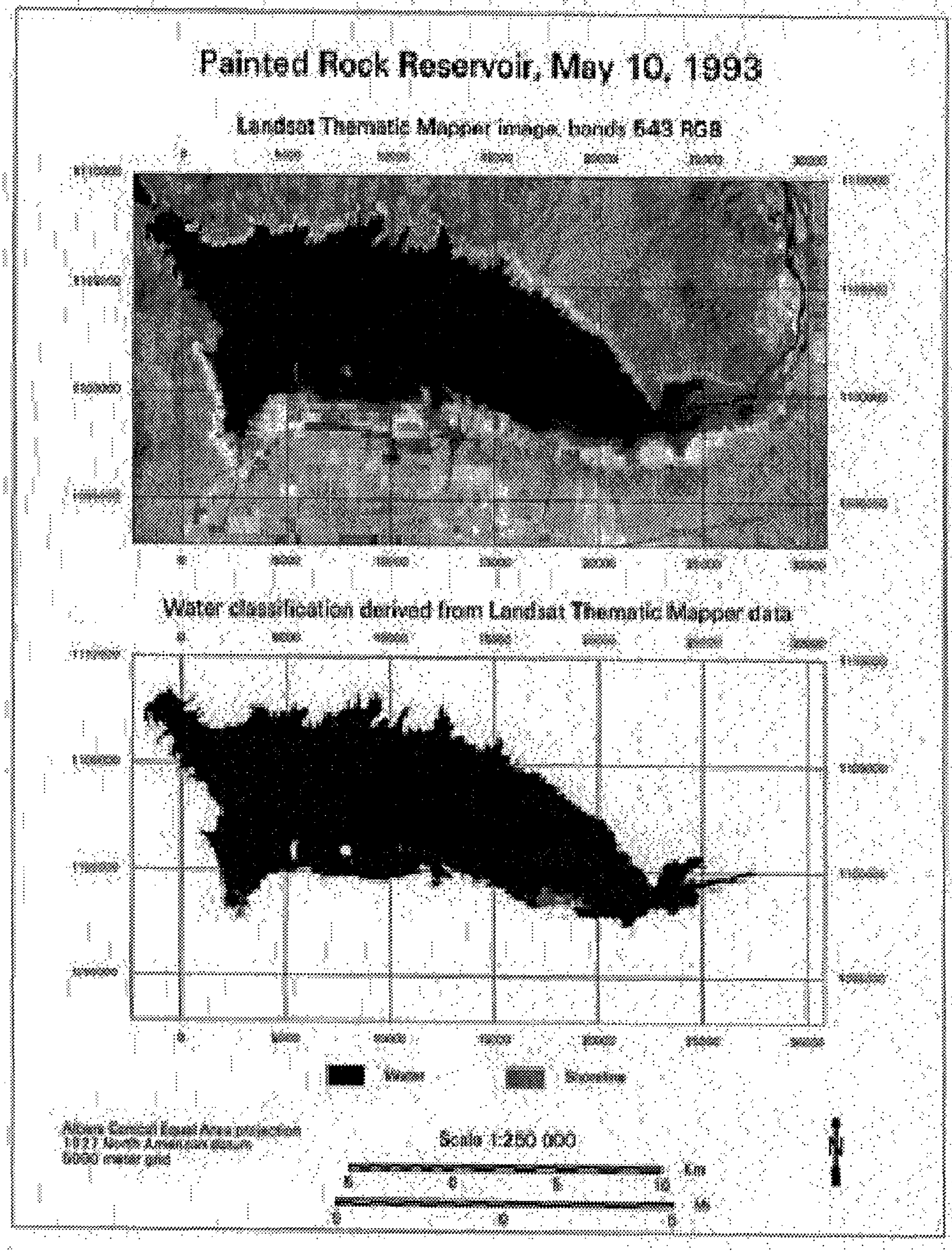
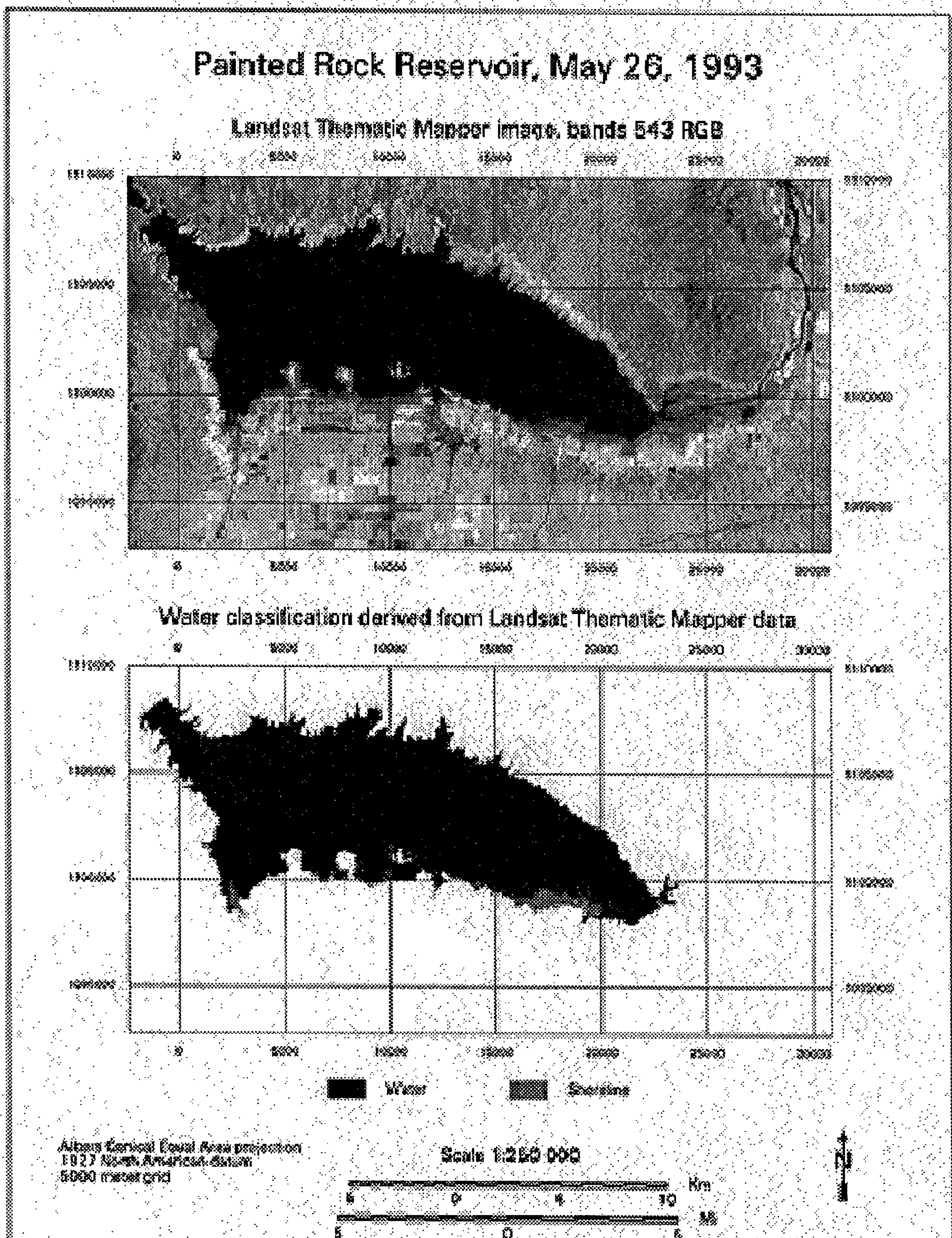
Km
5 0 5 10
Mi
5 0 5


Painted Rock Reservoir, May 10, 1993
Landsat Thematic Mapper image
Water classification derived from Landsat Thematic Mapper data
Scale 1:250 000
Km
Mi


Painted Rock Reservoir, May 26, 1993
Landsat Thematic Mapper image, bands 543 RGB
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Shoreline
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5000 meter grid
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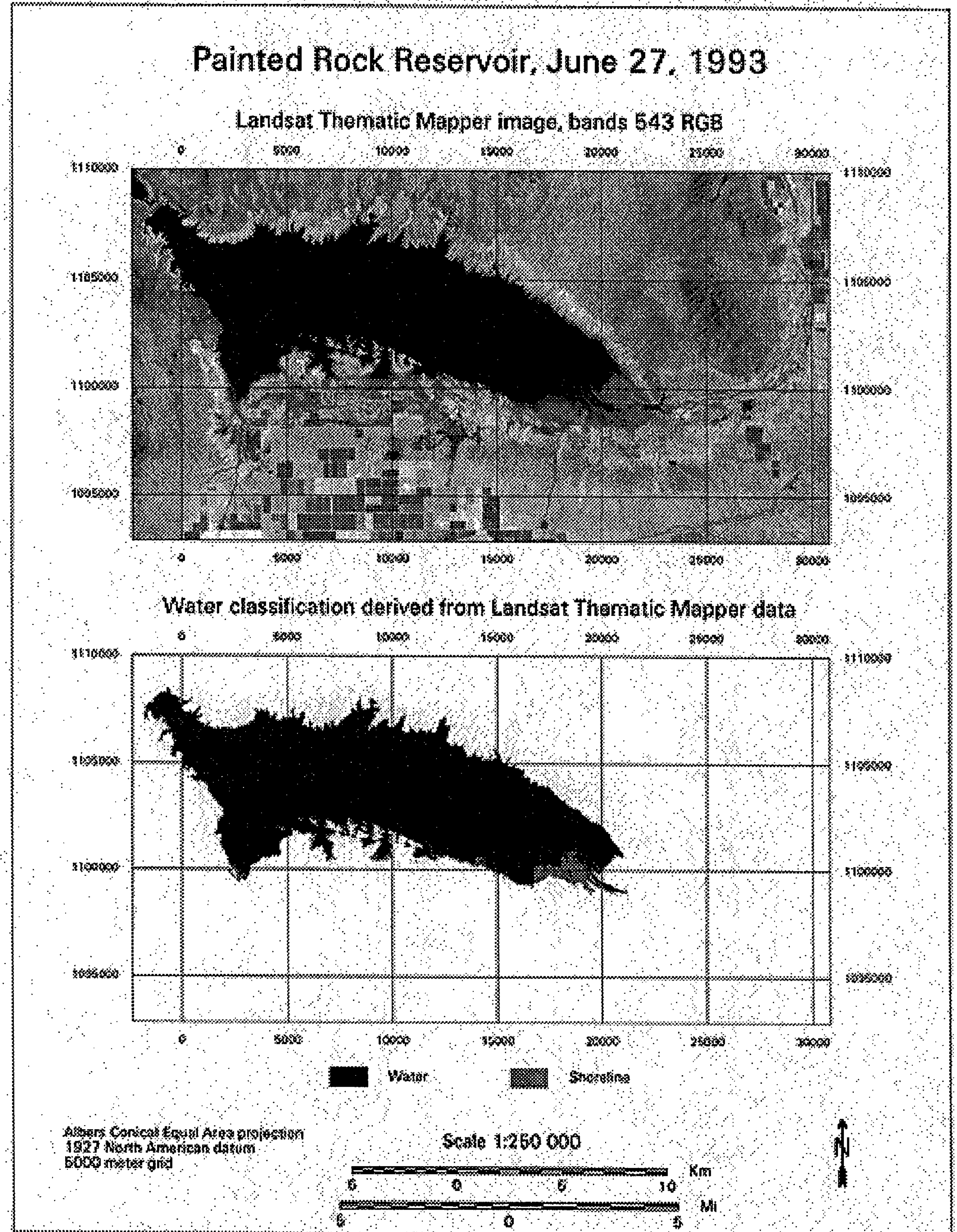
Km
Mi
N


Painted Rock Reservoir, June 27, 1993
Landsat Thematic Mapper image, bands 543 RGB
Water classification derived from Landsat Thematic Mapper data
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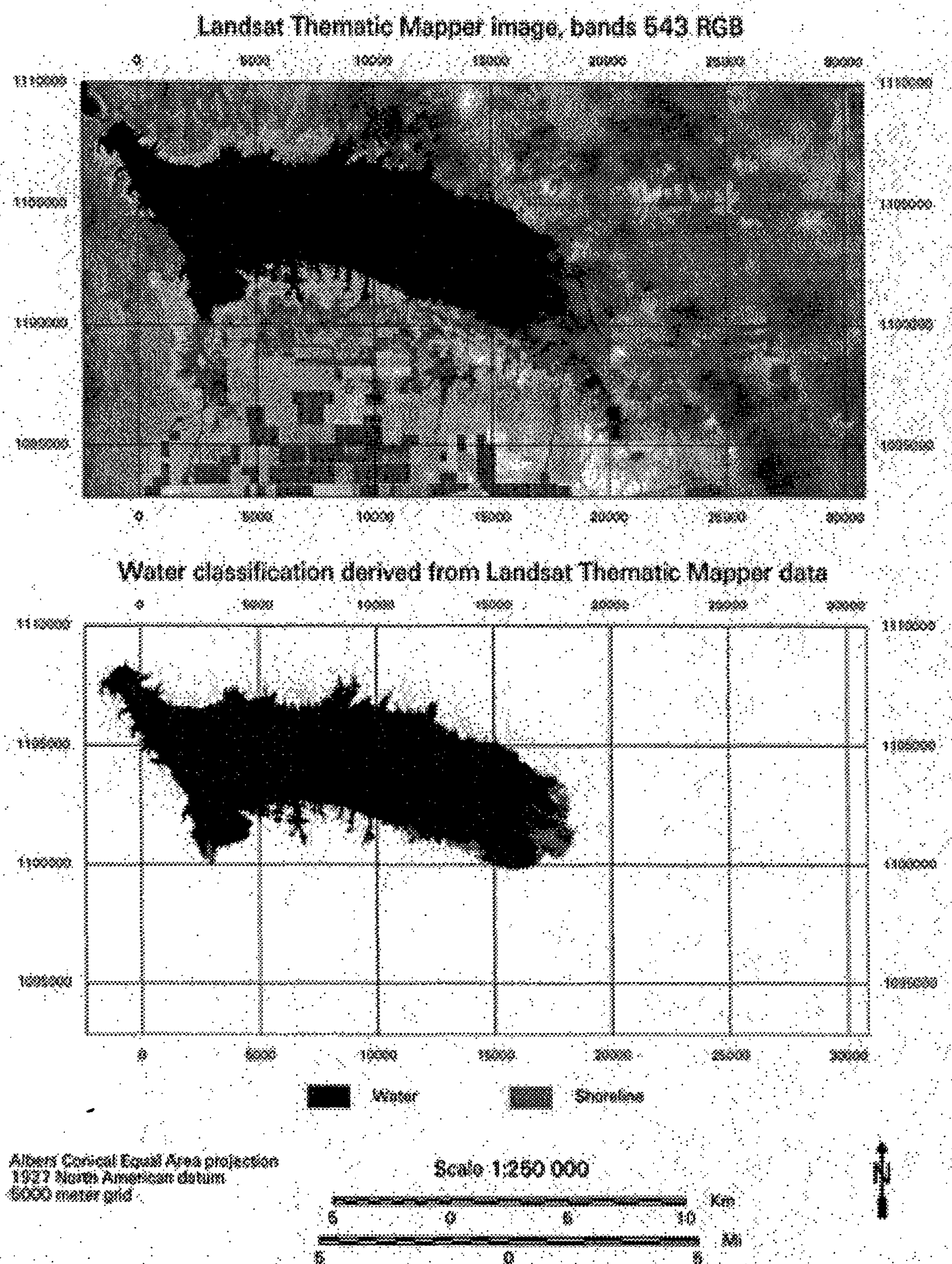
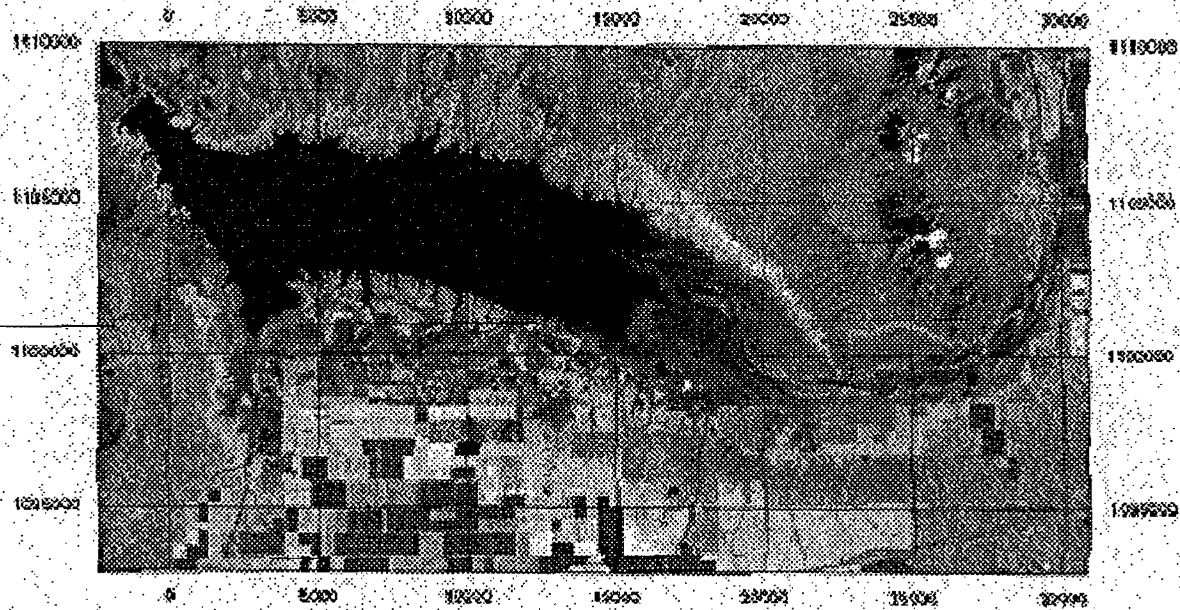
25000
30000
Water
Shoreline
Albers Conical Equal Area projection
1927 North American datum
5000 meter grid
Scale 1:250 000
Km
Mi
N

Painted Rock Reservoir, July 29, 1993

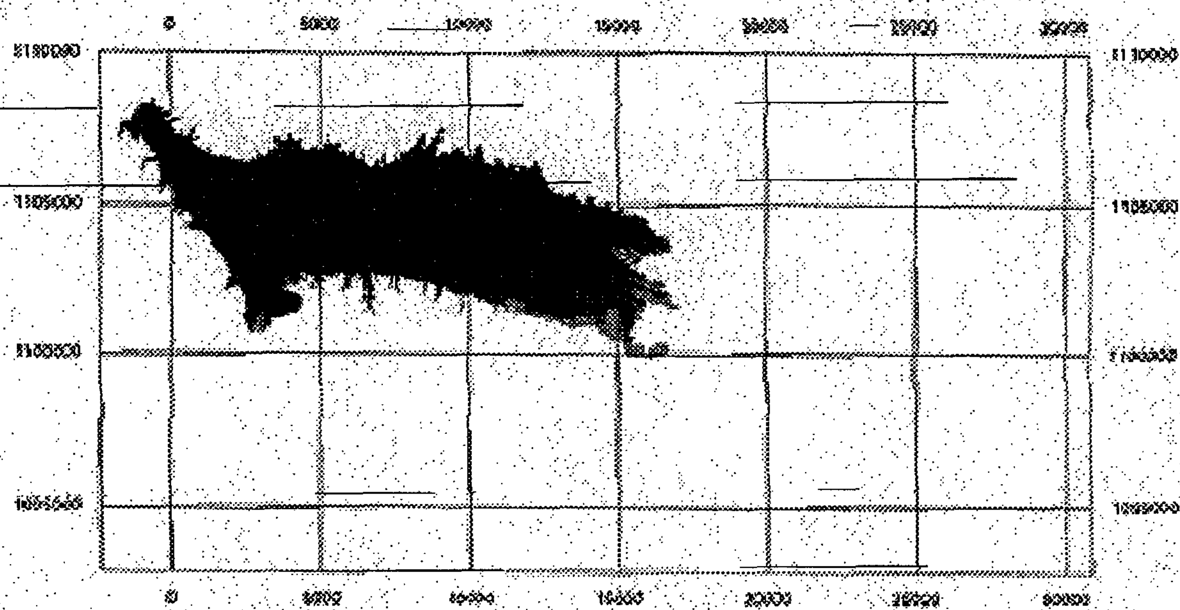


Painted Rock Reservoir, August 30, 1993

Landsat Thematic Mapper image, bands 543 RGB



Water classification derived from Landsat Thematic Mapper data



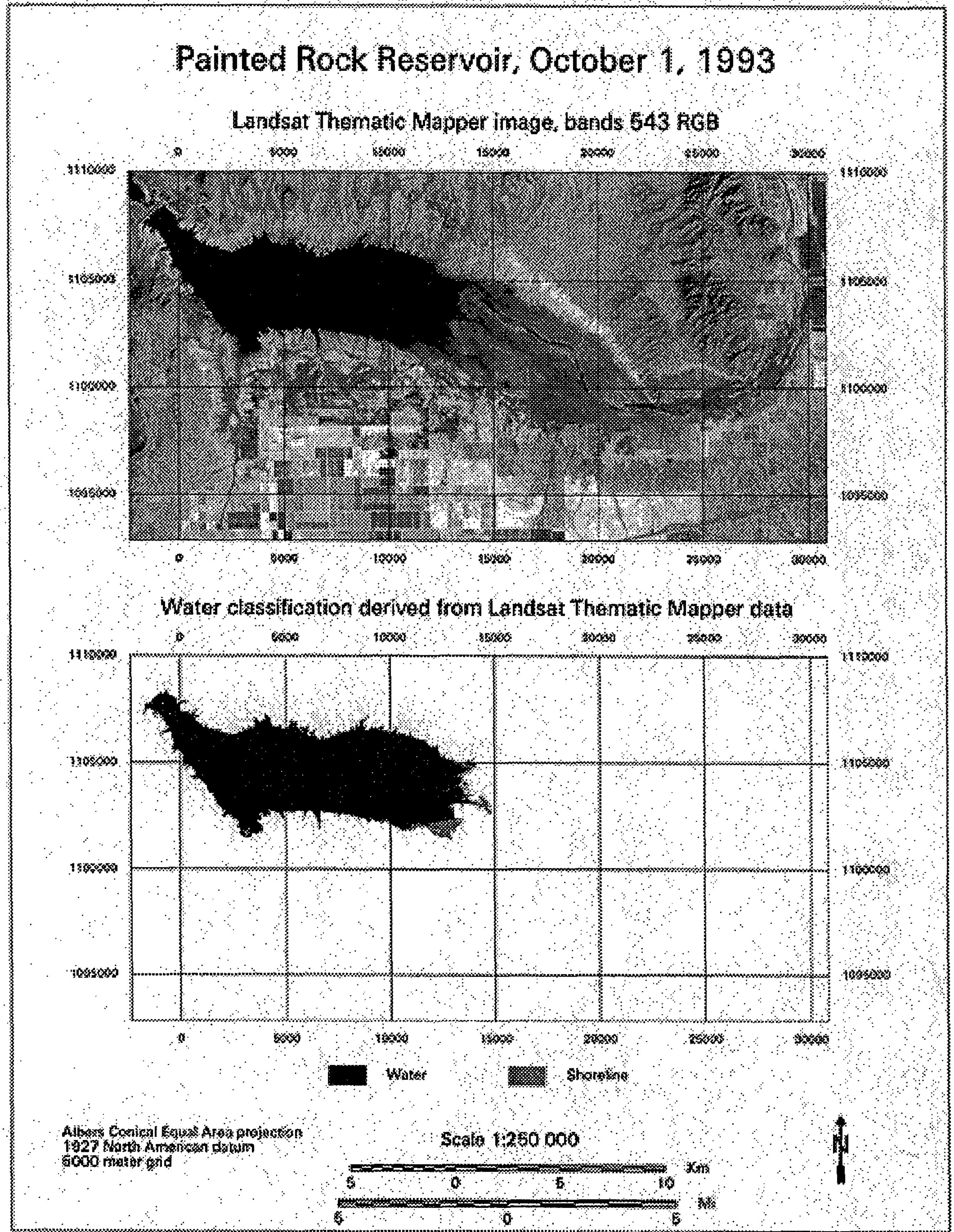
Water Shoreline

Albers Conical Equal Area projection
1927 North American datum
5000 meter grid

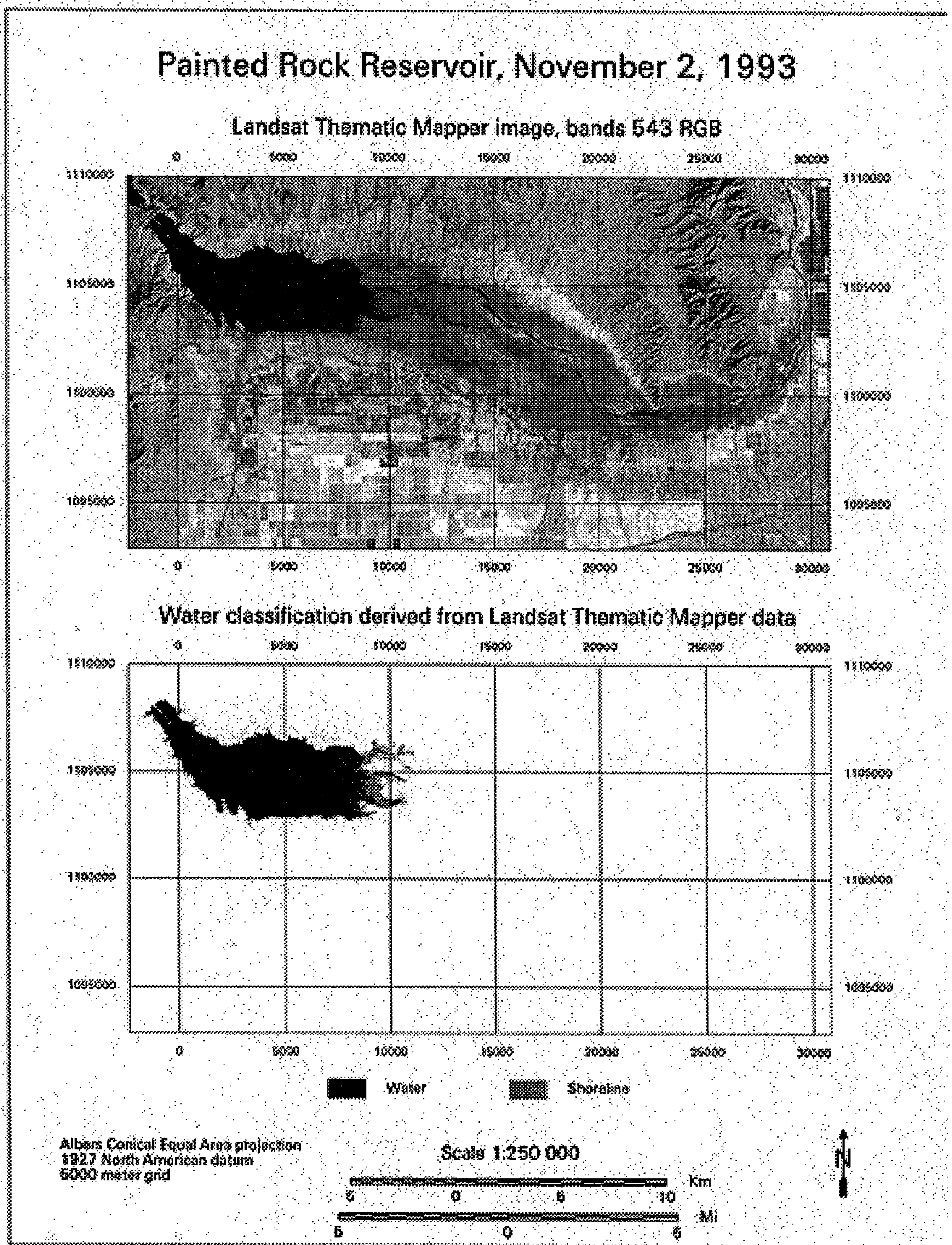
Scale 1:250 000

Km: 5 0 5 10

Mi: 5 0 5

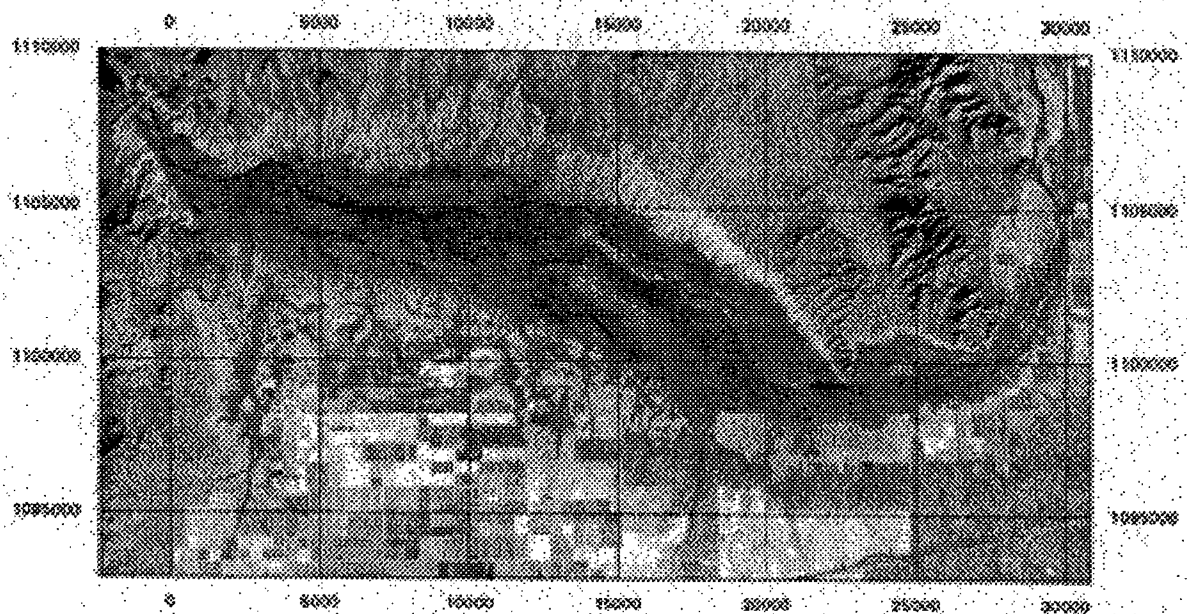


Painted Rock Reservoir, October 1, 1993
Landsat Thematic Mapper image, bands 543 RGB
Water classification derived from Landsat Thematic Mapper data
Water
Shoreline
Albers Conical Equal Area projection
1927 North American datum
5000 meter grid
Scale 1:250 000
Km
Mi

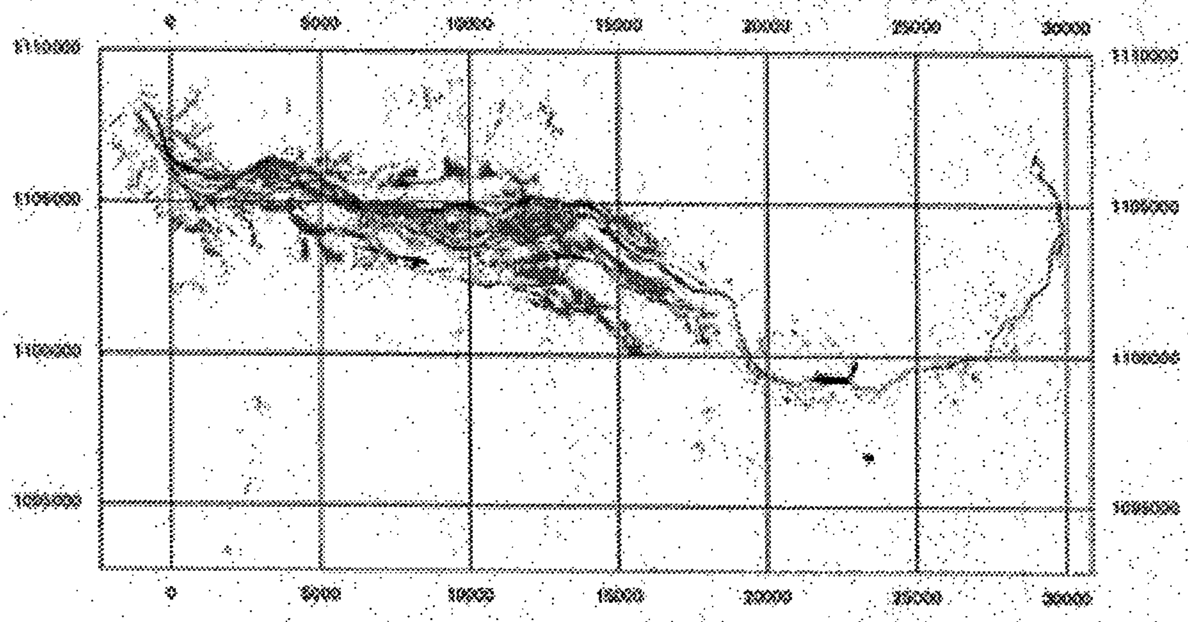

Painted Rock Reservoir, November 2, 1993
Landsat Thematic Mapper image, bands 543 RGB
Water classification derived from Landsat Thematic Mapper data
0
5000
10000
15000
20000
25000
30000
1110000
1105000
1100000
1095000
Water
Shoreline
Albers Conical Equal Area projection
1927 North American datum
5000 meter grid
Scale 1:250 000
Km
Mi
N

Painted Rock Reservoir, December 4, 1993

Landsat Thematic Mapper image, bands 543 RGB



Water classification derived from Landsat Thematic Mapper data



Water   Shoreline

Albers Conical Equal Area projection
1927 North American datum
5000 meter grid

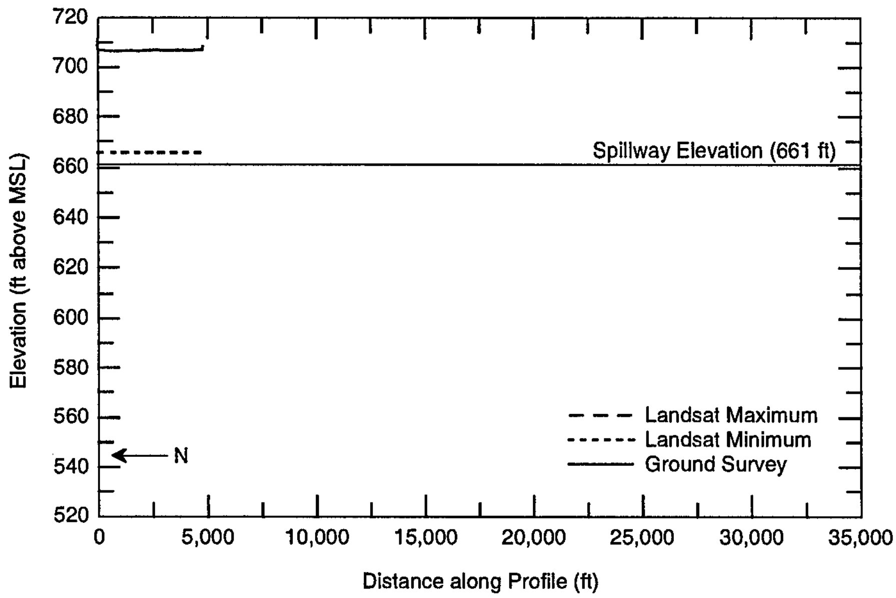
Scale 1:250,000

Km: 5 0 5 10

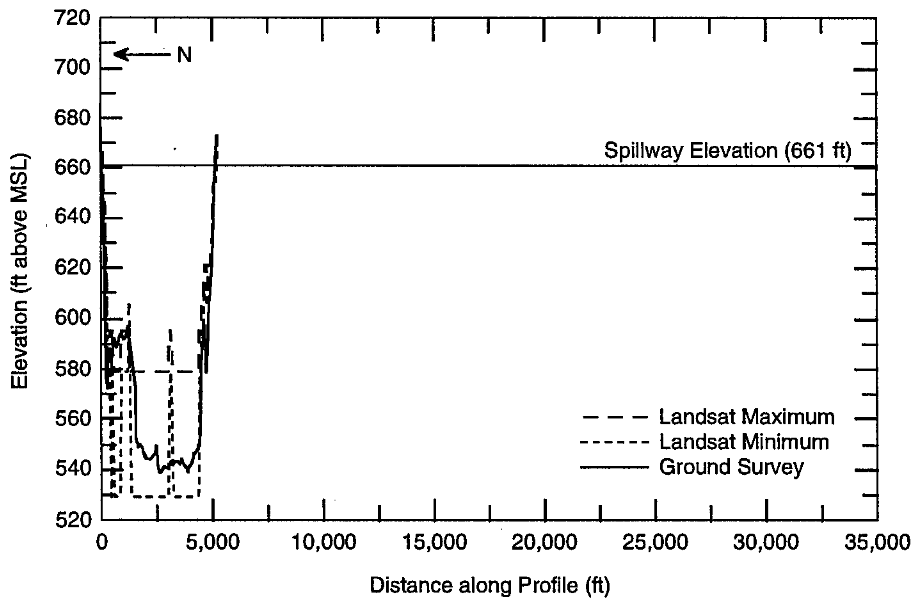
Mi: 5 0 5

N

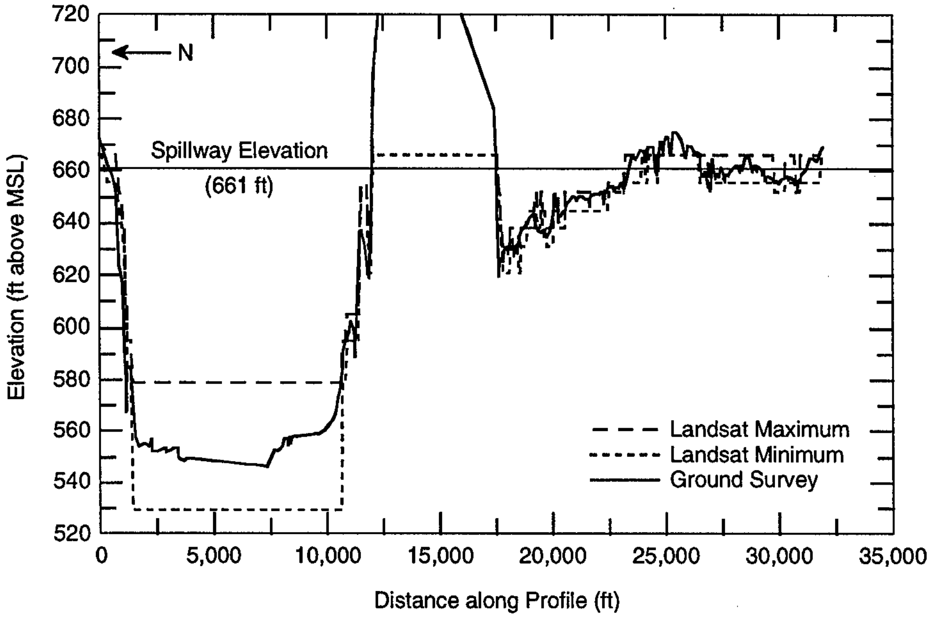
APPENDIX B: CROSS SECTIONS OF GROUND SURVEY PROFILES



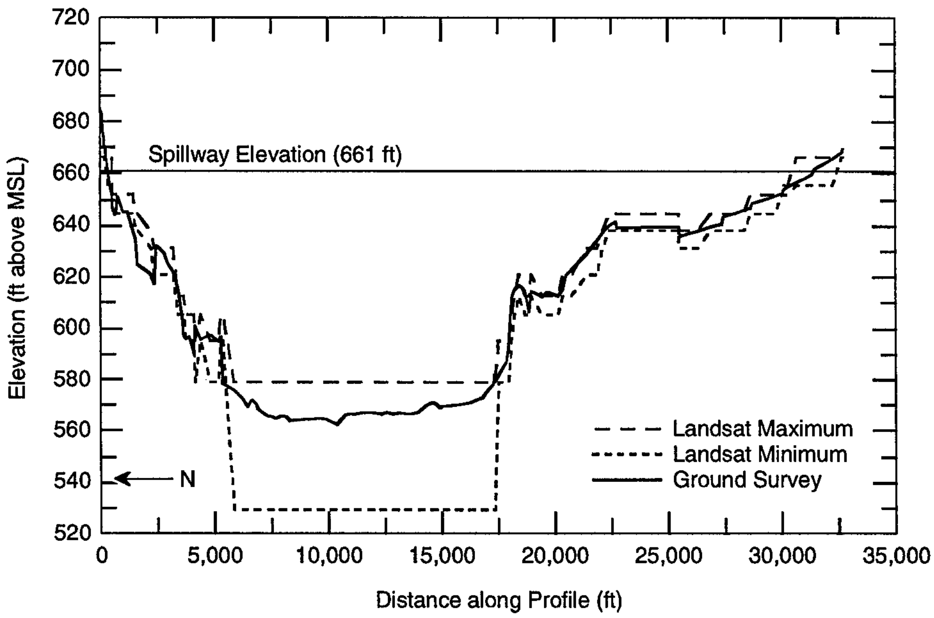
Profile #1.



Profile #2.



Profile #3.



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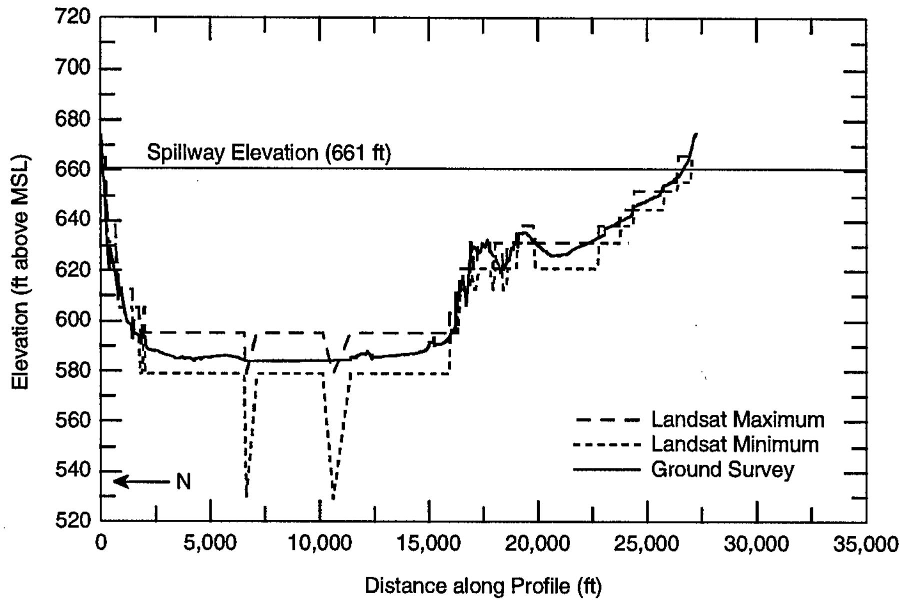
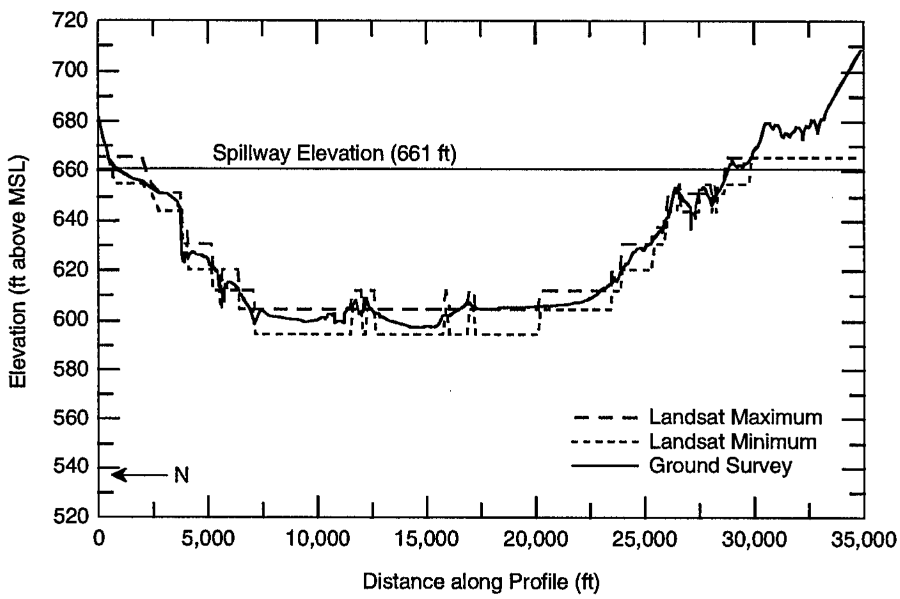
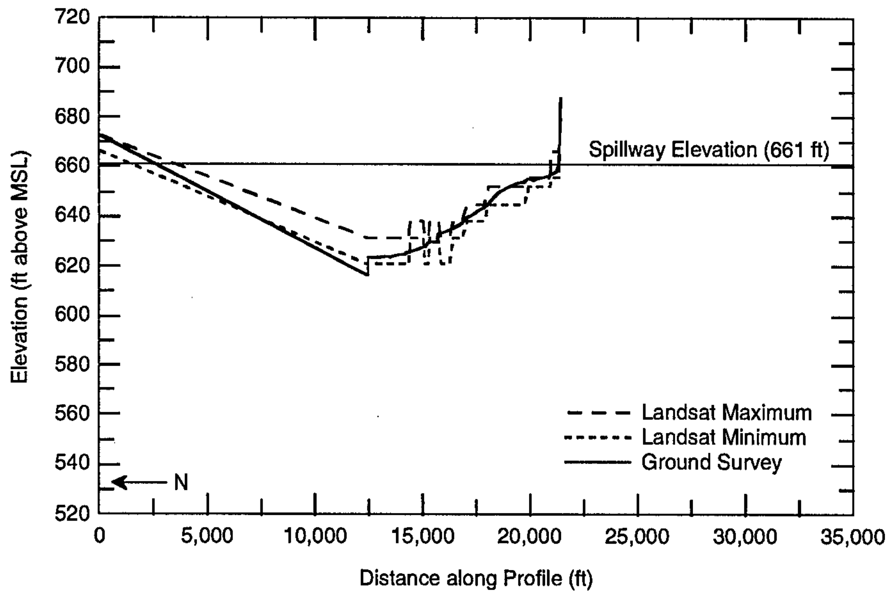


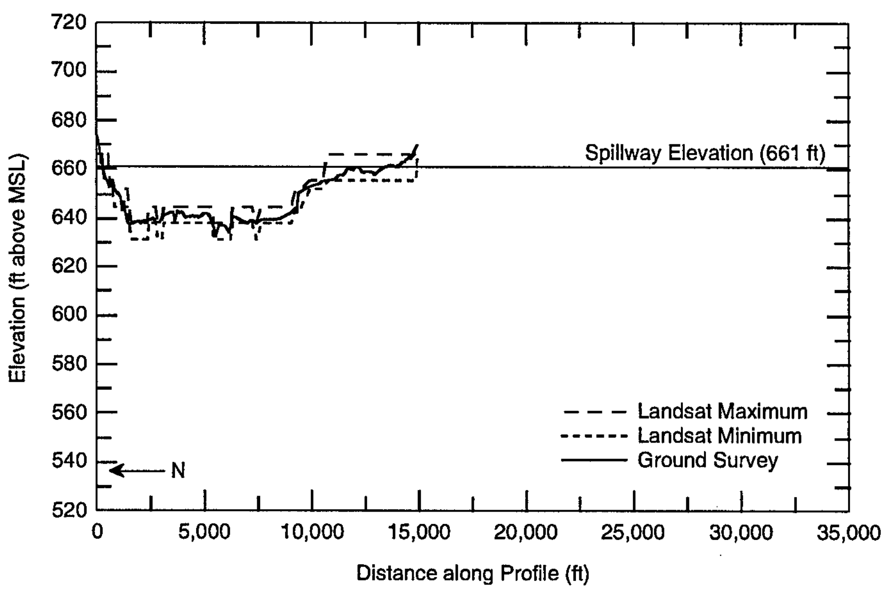
Profile #5.



Profile #6



Profile #7.



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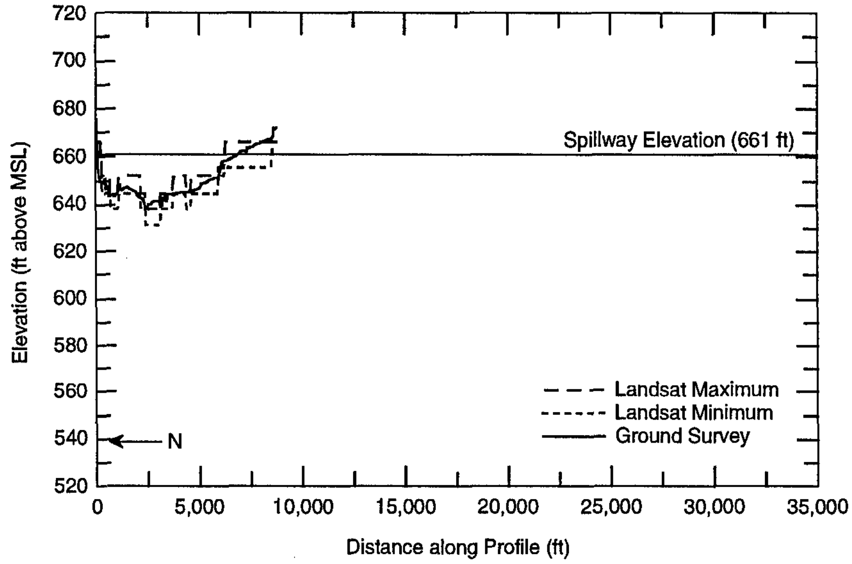
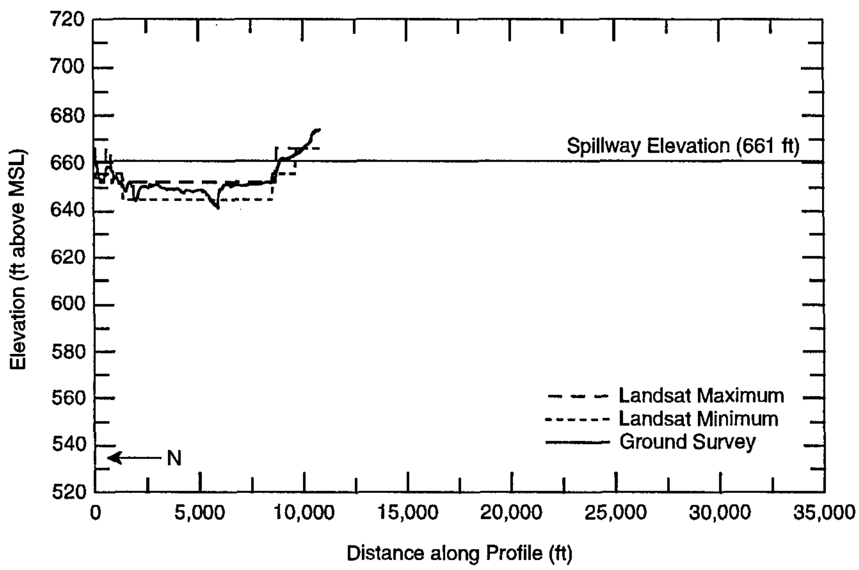
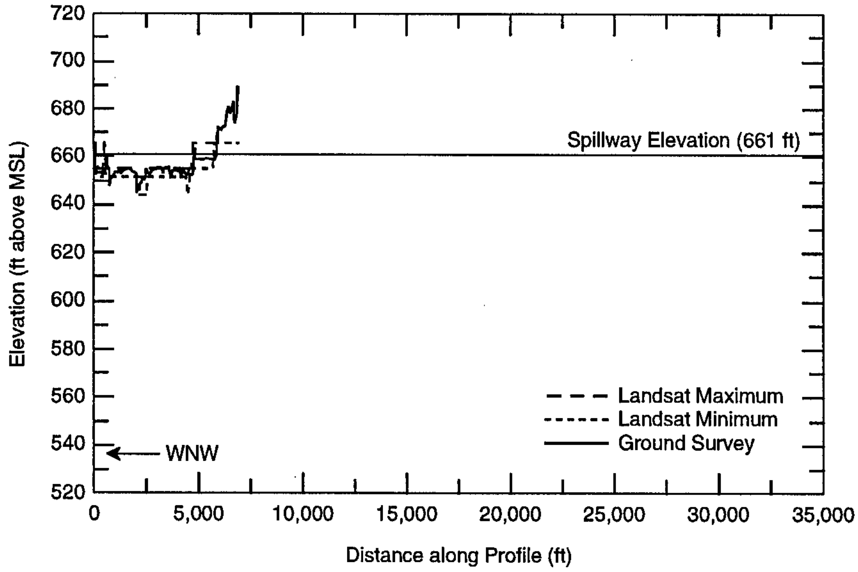


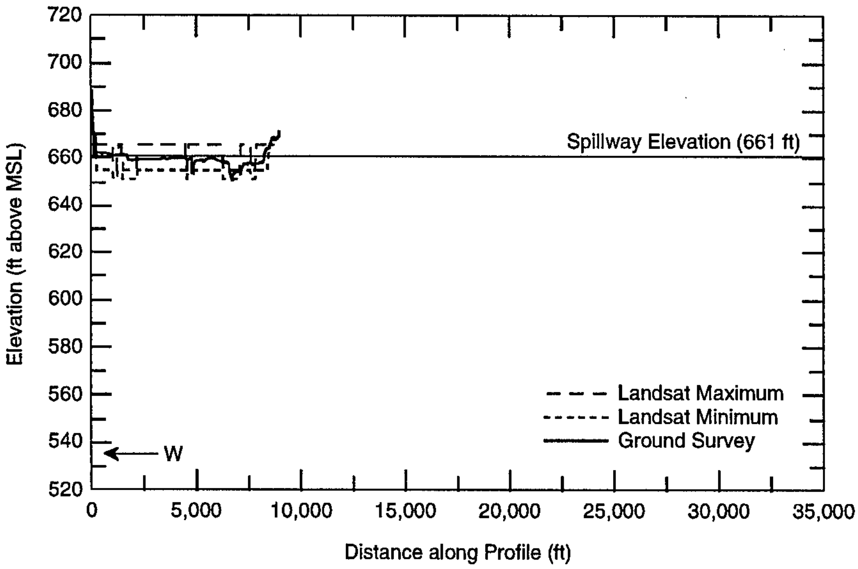
Profile #9.



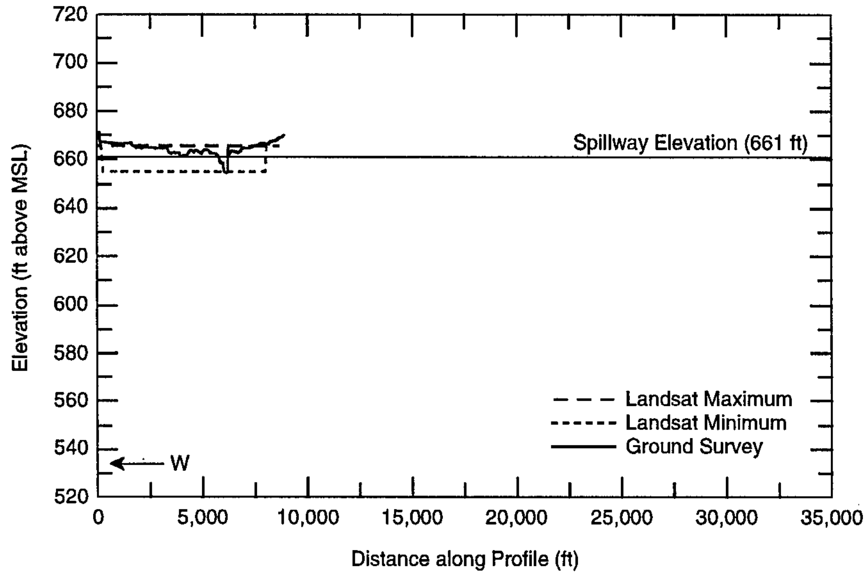
Profile #10.



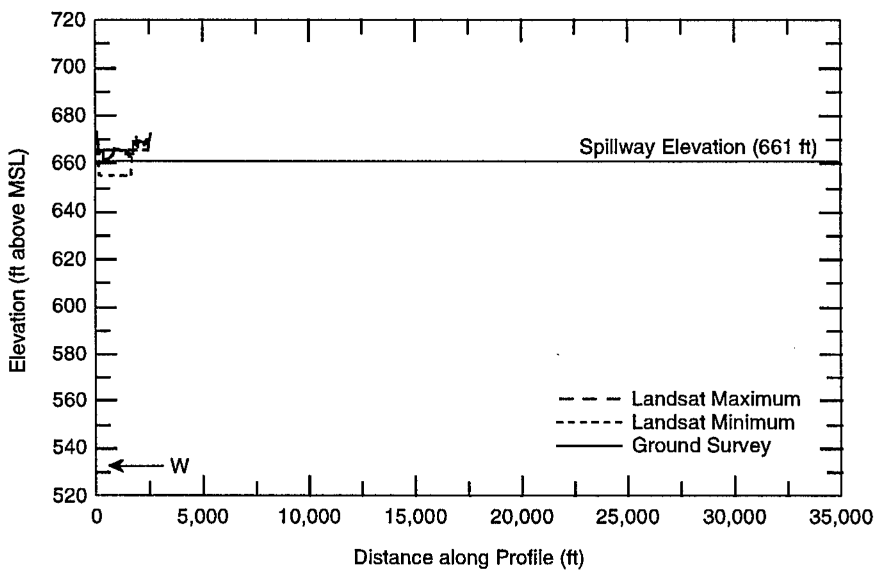
Profile #11.



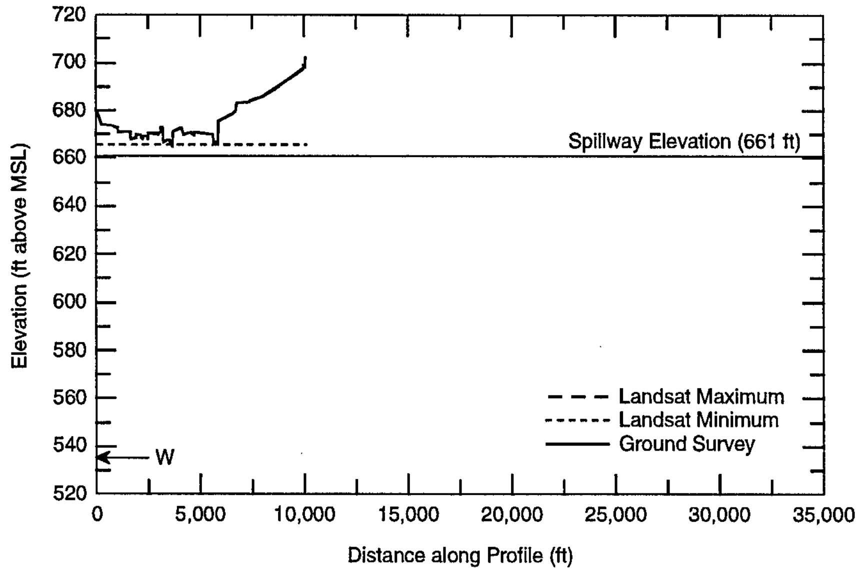
Profile #12.



Profile #13.



Profile #14.



720
700
680
660
640
620
600
580
560
540
520
Elevation (ft above MSL)
W
Spillway Elevation (661 ft)
Landsat Maximum
Landsat Minimum
Ground Survey
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
Distance along Profile (ft)

Profile #15.

APPENDIX C: SURFACE AREA AND STORAGE CAPACITY TABLES

Table C1 lists the Painted Rock Reservoir elevation vs. water surface area from 1953 and 1985 surveys and from the 1993 Landsat estimate, and for a hypothetical 500,000-acre-ft loss. The 1953 area is from a file provided by Gregory Peacock of the Los Angeles District. These values are presumed to be those that were computed from an aerial survey of March 1953; 1985 area is from a table that was computed in 1993 and supplied by the Los Angeles District.

Table C2 lists the Painted Rock Reservoir storage capacity from 1953 and 1985 surveys, from the 1993 Landsat estimates, and for a hypothetical 500,000-acre-ft loss.

The 1953 capacity is also from a file provided by Mr. Peacock, and the 1985 capacity is from a file printout, "GILA RIVER/PTRK/ELEV-STOR" (same as Reservoir Regulation Manual [USACE 1962], Table 13, which was computed in 1987. This manual has incorporated changes and additions, but it retains its original publication date.)

Table C1. Painted Rock Reservoir elevation vs. water surface area as of 1953 and 1985 surveys, 1993 Landsat estimate, and a hypothetical 500,000-acre-ft loss.

Elevation (ft above MSL)	*Surface area (acres)* 1953 (survey)	1985 (survey)	1993 (Landsat)	*500,000 acre-ft-loss scenario*	*Surface area loss (acres)* 1953 to 1993	1985 to 1993	Notes
530	27	0	0	0	27	0	*
532	108	31	0	0	108	31	*
534	189	62	0	0	189	62	*
536	270	88	0	0	270	88	*
538	351	107	0	0	351	107	*
540	432	127	0	0	432	127	*
542	575	151	0	0	575	151	*
544	718	176	0	0	718	176	*
546	922	274	0	0	922	274	*
548	1,190	447	143	122	1,047	304	
550	1,450	620	282	240	1,168	338	
552	1,790	1,123	751	641	1,039	372	
554	2,130	1,626	1,220	1,041	910	406	
556	2,470	2,043	1,603	1,368	867	440	
558	2,810	2,373	1,899	1,620	911	474	
560	3,150	2,703	2,196	1,873	954	507	
562	3,650	3,081	2,540	2,166	1,110	541	
564	4,150	3,458	2,883	2,459	1,267	575	
566	4,680	3,981	3,372	2,877	1,308	609	
568	5,250	4,649	4,006	3,417	1,244	643	
570	5,800	5,317	4,640	3,958	1,160	677	
572	6,370	6,145	5,435	4,636	935	710	
574	6,920	6,974	6,230	5,314	690	744	
576	7,590	7,733	6,955	5,933	635	778	
578	8,370	8,423	7,611	6,493	759	812	
578.51	8,571	8,599	7,779	6,636	793	821	2 Nov 98
580	9,160	9,113	8,180	6,978	980	933	

* 1993 Landsat area value was set to zero because interpolation value was negative.

Table C1 (cont'd).

Elevation (ft above MSL)	*Surface area (acres)* 1953 (survey)	1985 (survey)	1993 (Landsat)	*500,000 acre-ft-loss scenario*	*Surface area loss (acres)* 1953 to 1993	1985 to 1993	*Notes*
582	9,890	9,945	8,861	7,559	1,029	1,084	
584	10,600	10,777	9,542	8,140	1,058	1,235	
586	11,400	11,641	10,255	8,748	1,145	1,386	
588	12,300	12,538	11,001	9,385	1,299	1,537	
590	13,100	13,435	11,747	10,021	1,353	1,688	
592	13,900	14,266	12,427	10,601	1,473	1,839	
594	14,700	15,097	13,108	11,181	1,592	1,989	
594.65	14,960	15,367	13,328	11,369	1,632	2,039	1 Oct 93
596	15,500	15,934	13,910	11,866	1,590	2,024	
598	16,300	16,778	14,775	12,604	1,525	2,003	
600	17,100	17,622	15,641	13,342	1,459	1,981	
602	18,300	18,413	16,453	14,035	1,847	1,960	
604	19,400	19,204	17,265	14,728	2,135	1,939	
604.88	19,840	19,552	17,623	15,033	2,217	1,929	30 August 93
606	20,400	20,101	18,180	15,508	2,220	1,921	
608	21,200	21,102	19,195	16,374	2,005	1,907	
610	22,100	22,104	20,211	17,241	1,889	1,893	
612	23,200	23,162	21,283	18,155	1,917	1,879	
612.32	23,376	23,332	21,455	18,302	1,921	1,877	29 July 93
614	24,300	24,221	22,351	19,067	1,949	1,870	
616	25,300	25,280	23,418	19,977	1,882	1,862	
618	26,400	26,341	24,488	20,889	1,912	1,853	
620	27,400	27,401	25,556	21,801	1,844	1,845	
620.61	27,736	27,730	25,888	22,084	1,847	1,842	27 June 93
622	28,500	28,481	26,723	22,796	1,777	1,758	
624	29,600	29,560	27,923	23,820	1,677	1,637	
626	30,700	30,643	29,128	24,847	1,572	1,515	
628	31,800	31,729	30,335	25,877	1,465	1,394	
630	32,800	32,815	31,542	26,907	1,258	1,273	
631.06	33,489	33,512	32,303	27,556	1,186	1,208	26 May 93
632	34,100	34,129	32,890	28,057	1,210	1,239	
634	35,300	35,443	34,138	29,122	1,162	1,305	
636	36,600	36,759	35,388	30,188	1,212	1,371	
637.75	37,825	37,913	36,485	31,123	1,340	1,428	10 May 93
638	38,000	38,078	36,662	31,274	1,338	1,416	
640	39,400	39,397	38,075	32,479	1,325	1,322	
642	40,500	40,658	39,429	33,635	1,071	1,229	
644	41,600	41,919	40,784	34,791	816	1,135	
644.22	41,732	42,059	40,934	34,919	798	1,124	24 April 93
646	42,800	43,181	42,074	35,891	726	1,107	
648	44,300	44,444	43,357	36,985	943	1,087	
650	45,700	45,706	44,638	38,079	1,062	1,068	
651.68	46,792	46,846	45,795	39,066	997	1,051	8 April 93
652	47,000	47,064	46,051	39,283	949	1,013	
654	48,300	48,421	47,644	40,643	656	777	
655.24	49,106	49,263	48,633	41,486	473	630	31 March 93
656	49,600	49,781	49,087	41,874	513	694	
658	51,100	51,142	50,281	42,892	819	861	
660	52,500	52,504	51,475	43,911	1,025	1,029	
661	53,200	53,213	52,101	44,444	1,099	1,112	spillway
662	53,900	53,922	52,726	44,978	1,174	1,196	
664	55,300	55,341	53,978	46,045	1,322	1,363	
665.86	56,602	56,660	55,141	47,038	1,461	1,519	7 March 93
666	56,700	56,759					

Table C1 (cont'd). Painted Rock Reservoir elevation vs. water surface area as of 1953 and 1985 surveys, 1993 Landsat estimate, and a hypothetical 500,000-acre-ft loss.

Elevation (ft above MSL)	Surface area (acres) 1953 (survey)	1985 (survey)	1993 (Landsat)	500,000 acre-ft-loss scenario	Surface area loss (acres) 1953 to 1993	1985 to 1993	Notes
668	58,100	58,178					
670	59,600	59,596					
672	60,900	60,958					
674	62,200	62,319					
676	63,600	63,687					
678	65,000	65,062					
680	66,400	66,436					
682	68,200	68,202					
684	69,900	69,967					
686	71,700	71,742					
688	73,500	73,527					
690	75,300	75,311					
692	77,300	77,267					
694	79,200	79,222					
696	81,200	81,181					
698	83,100	83,142					
700	85,100	85,103					
702		86,902					
704		88,701					

* 1993 Landsat area value was set to zero because interpolation value was negative.

Table C2. Painted Rock Reservoir storage capacity from 1953 and 1985 surveys, 1993 Landsat estimate, and 500,000-acre-ft-loss scenario.

Elevation (ft above MSL)	*Storage capacity (acre-ft)* 1953 (survey)	*Storage capacity (acre-ft)* 1985 (survey)	*Storage capacity (acre-ft)* 1993 (Landsat)	*500,000 acre-ft-loss scenario*	*Storage capacity (acre-ft)* 1953 to 1993	*Storage capacity (acre-ft)* 1985 to 1993	Notes
530	83	0	0	0	83	0	
532	250	31	0	0	250	31	
534	560	125	0	0	560	125	
536	990	278	0	0	990	278	
538	1,580	473	0	0	1,580	473	
540	2,320	708	0	0	2,320	708	
542	3,360	986	0	0	3,360	986	
544	4,700	1,313	0	0	4,700	1,313	
546	6,400	1,726	0	0	6,400	1,726	
548	8,600	2,448	143	122	8,457	2,305	
550	11,700	3,515	567	483	11,133	2,948	
552	15,400	5,258	1,599	1,364	13,801	3,659	
554	19,500	8,008	3,570	3,046	15,930	4,438	
556	24,000	11,720	6,393	5,454	17,607	5,327	
558	29,100	16,137	9,896	8,442	19,204	6,241	
560	34,700	21,213	13,991	11,935	20,709	7,222	
562	42,200	26,996	18,726	15,974	23,474	8,270	
564	49,200	33,535	24,149	20,600	25,051	9,386	
566	58,100	40,902	30,404	25,936	27,696	10,498	
568	68,200	49,531	37,782	32,230	30,418	11,749	
570	79,500	59,498	46,428	39,606	33,072	13,070	
572	91,700	70,960	56,503	48,200	35,197	14,457	
574	105,000	84,079	68,168	58,150	36,832	15,911	
576	119,800	98,820	81,352	69,397	38,448	17,468	
578	136,200	114,976	95,918	81,823	40,282	19,058	
578.51	140,816	119,317	99,843	85,171	40,973	19,475	2 November 93
580	154,300	132,513	111,732	95,313	42,568	20,781	
582	174,000	151,570	128,773	109,850	45,227	22,797	
584	194,000	172,292	147,176	125,548	46,824	25,116	
586	216,000	194,695	166,974	142,436	49,026	27,721	
588	239,000	218,874	188,230	160,569	50,770	30,644	
590	265,600	244,848	210,979	179,975	54,621	33,869	
592	292,000	272,548	235,154	200,597	56,846	37,394	
594	318,000	301,911	260,688	222,380	57,312	41,223	
594.65	327,750	311,811	269,280	229,709	58,470	42,532	1 October 93
596	348,000	332,938	287,666	245,393	60,334	45,272	
598	381,000	365,650	316,351	269,862	64,649	49,299	
600	416,800	400,050	346,766	295,808	70,034	53,284	
602	453,000	436,085	378,860	323,186	74,140	57,225	
604	490,000	473,703	412,578	351,949	77,422	61,125	
604.88	507,600	490,756	427,929	365,044	79,671	62,827	30 August 93
606	530,000	512,955	447,978	382,147	82,022	64,977	
608	571,000	554,159	485,353	414,029	85,647	68,806	
610	613,300	597,365	524,758	447,644	88,542	72,607	
612	657,000	642,631	566,252	483,040	90,748	76,379	
612.32	664,360	650,071	573,090	488,873	91,270	76,981	29 July 93
614	703,000	690,015	609,887	520,263	93,113	80,128	
616	751,000	739,515	655,656	559,306	95,344	83,859	
618	802,000	791,136	703,562	600,173	98,438	87,574	
620	861,000	844,878	753,606	642,863	107,394	91,272	

Table C2 (cont'd).

Elevation (ft above MSL)	*Storage capacity (acre-ft)* 1953 (survey)	1985 (survey)	1993 (Landsat)	*500,000 acre-ft-loss scenario*	*Storage capacity (acre-ft)* 1953 to 1993	1985 to 1993	*Notes*
620.61	878,995	861,693	769,297	656,247	109,698	92,396	27 June 93
622	920,000	900,759	805,862	687,439	114,138	94,897	
624	978,000	958,800	860,508	734,055	117,492	98,292	
626	1,036,000	1,019,002	917,559	782,722	118,441	101,443	
628	1,098,000	1,081,374	977,022	833,447	120,978	104,352	
630	1,162,500	1,145,918	1,038,899	886,231	123,601	107,019	
631.06	1,197,215	1,181,071	1,072,738	915,097	124,477	108,333	26 May 93
632	1,228,000	1,212,862	1,103,378	941,235	124,622	109,484	
634	1,295,000	1,282,434	1,170,406	998,413	124,594	112,028	
636	1,366,000	1,354,635	1,239,933	1,057,723	126,067	114,702	
637.75	1,434,250	1,419,975	1,302,822	1,111,370	131,428	117,152	10 May 93
638	1,444,000	1,429,472	1,311,966	1,119,170	132,034	117,506	
640	1,523,400	1,506,948	1,386,702	1,182,924	136,698	120,246	
642	1,603,000	1,587,003	1,464,206	1,249,038	138,794	122,797	
644	1,683,000	1,669,580	1,544,420	1,317,465	138,580	125,160	
644.22	1,691,910	1,678,818	1,553,409	1,325,133	138,501	125,409	24 April 93
646	1,764,000	1,754,681	1,627,287	1,388,154	136,713	127,394	
648	1,854,000	1,842,305	1,712,717	1,461,030	141,283	129,588	
650	1,948,800	1,932,455	1,800,713	1,536,095	148,087	131,742	
651.68	2,029,608	2,010,199	1,876,677	1,600,896	152,931	133,522	8 April 93
652	2,045,000	2,025,225	1,891,372	1,613,432	153,628	133,853	
654	2,142,000	2,120,709	1,985,067	1,693,358	156,933	135,642	
655.24	2,202,760	2,181,275	2,044,759	1,744,278	158,001	136,516	31 March 93
656	2,240,000	2,218,910	2,081,892	1,775,954	158,108	137,018	
658	2,340,000	2,319,834	2,181,260	1,860,720	158,740	138,574	
660	2,440,200	2,423,480	2,283,016	1,947,522	157,184	140,464	
661	2,491,700	2,476,339	2,334,804	1,991,700	156,896	141,535	spillway*
662	2,543,000	2,529,906	2,387,217	2,036,411	155,783	142,689	
664	2,650,000	2,639,170	2,493,920	2,127,434	156,080	145,250	
665.86	2,755,090	2,743,331	2,595,400	2,214,001	159,690	147,931	7 March 93
666	2,763,000	2,751,270					
668	2,880,000	2,866,206					
670	3,006,000	2,983,980					
672	3,122,000	3,104,534					
674	3,246,000	3,227,810					
676	3,372,000	3,353,814					
678	3,500,000	3,482,562					
680	3,630,500	3,614,060					
682	3,763,000	3,748,698					
684	3,900,000	3,886,866					
686	4,042,000	4,028,571					
688	4,189,000	4,173,840					
690	4,339,000	4,322,678					
692	4,492,000	4,475,255					
694	4,649,000	4,631,744					
696	4,810,000	4,792,145					
698	4,974,000	4,956,468					
700	5,141,000	5,124,713					
702		5,296,717					
704		5,472,320					

* Spillway capacity for 1953 as listed in Reservoir Regulation Manual; interpolated value = 2,491,600.

APPENDIX D: SOURCES OF UNCERTAINTY AND ERROR ANALYSIS

Sources of uncertainty in the Landsat estimate of surface area and storage capacity are explained below.

Mudflats (#1)

The Landsat scenes classified using TM Bands 4 and 5, as described in the Water Classification section, had three classes: water, shoreline, and land. The concern here is the shoreline class. One would expect the shoreline class to be composed of just edge pixels, which include part water and part land, and thus trace a one-pixel-wide rim encircling the reservoir. This does happen in many parts of the reservoir, but there are parts, especially at the upper end of the reservoir, where the shoreline class is extensive (for instance, p. 24, the classification of the 27 June 1993 scene). The hypothesis is that these extensive shoreline areas are mud flats or very shallow water. It is not clear whether these areas should be counted as water or land. To estimate the effect of this uncertainty on the storage capacity estimate, these extensive areas were isolated, and the water surface area was recomputed twice: once including them as 100% water, and again excluding them entirely from the surface area estimate. As can be seen in Table 13, the "mudflats" uncertainty is the largest one, affecting the capacity estimate by +40,000 or –30,000 acre-ft at spillway elevation.

Rectification (#2)

The 1993 surface area acreage values, and hence the storage capacity values, are dependent on the Landsat pixels being a known size, which is determined by the accuracy of the rectification procedure. This is dependent on how well each image is warped to match the model image (7 March 1993), how well the model image is warped to match the 1:100,000 scale DLG data, and the uncertainty in the 1:100,000-scale DLG data.

A given percent error in the pixel size for a Landsat scene translates into the same percentage error in the capacity estimate. The water surface area estimate has the same percent error, because the surface area is just the sum of the pixel areas. If it is assumed that all scenes have this same error, then each capacity increment also has the same percentage error, because it is the product of surface area and depth (unaffected by this error); the total capacity, because it is the sum of the increments, again has the same percentage error.

If it is assumed that the ground control points (GCPs) used in rectifying the data are in error by one pixel, it translates into a plus or minus 0.35% uncertainty in pixel area and thereby a (worst case) plus or minus 0.35% uncertainty in capacity.

If it is assumed that the uncertainty in the DLG data is the same as that for the 1:100,000-scale paper maps from which they are derived, as listed in the National Map Accuracy Standards (USGS 1998b), then 90% of well-defined points on the map should be within one-fiftieth of an inch of their true position at the scale of the map (50.8 m on the ground). If it is assumed that the map points used for GCPs in rectifying the model map to the DLG data are off (either too far out or too far in) by this amount, the pixel area uncertainty, and thereby the worst case capacity uncertainty, translates to 0.62%. The uncertainty due to digitization, 0.003 in. (7.62 m on the ground), was not considered.

Because the DLG uncertainty was the bigger, it was used in estimating the effect on storage capacity. At spillway elevation, this worst case uncertainty is plus or minus about 15,000 acre-ft.

Wind setup (#3)

In the above estimates, it was assumed that there was no wind setup and the water surface of the reservoir was level, and that the elevation readings taken at the dam hold for the whole reservoir. It is known that wind can affect this; if there is a west wind, for instance, then the elevation of the water surface at the east end of the reservoir will be higher than that at the west end, making a tilted rather than level water surface. The surface area for this tilted surface is assumed to be halfway between the area of level surface for the lower elevation and that for the higher elevation.

It is also assumed, for the purposes of making a quantitative estimate of the uncertainty due to wind setup, that

- The reservoir is an east-west rectangle with the sides parallel and perpendicular to the direction of the wind, with the dam at the west end of the rectangle.
- The amount of water surface elevation difference caused by wind is proportional to the fetch.
- The fetch is proportional to the elevation (above empty) of the reservoir.
- The maximum wind setup for a gale force wind on the full reservoir is 1-ft elevation.

With these assumptions, it is possible to estimate the possible surface elevation difference caused by wind setup for each Landsat scene/ reservoir elevation, and the corresponding new surface area value (for the tilted surface). In order to compute this, the difference in area for tilted surfaces vs. level surface was estimated, using the 1985 area table, because it has more detailed elevation data than the Landsat scenes. This 1985 area difference was then applied to the 1993 area figures to approximate what the effect on area would be for the 1993 scenes in the presence of wind setup.

As a single number approximation of the maximum uncertainty caused by wind setup, it was assumed that the wind was blowing at half gale force at the time of all the Landsat passes either west or east. If the wind was blowing west, the Landsat area estimates (and hence capacity estimates) would be too high and should be corrected downward, and if east, then corrected upward.

At spillway elevation (661 ft), the uncertainty in storage capacity caused by wind setup, as approximated above, is plus or minus about 8000 acre-ft.

Classification threshold (#4)

In calculation of water surface area, the 21 TM Band 5 brightness classes were split into water, shoreline, and land categories based on a visual assessment of the classification images. Although best judgment was used in these decisions, there is some uncertainty in the selection of these classification thresholds. There is also variation in the reflectance of the land from one part of the reservoir to another (bright white sediment vs. darker mudflats and medium soil), which means that ideally different thresholds should be chosen in different parts of the reservoir.

To estimate the effect of the classification threshold uncertainty on the storage capacity estimates, the water surface area was recomputed for each Landsat scene, moving both the water/ shoreline and the shoreline/land thresholds up one class to get an upper water surface area bound, and down one class for a lower bound. The storage capacity figures were then computed assuming that all the scenes had the upper bound of surface area, and then the lower bound. It is unlikely that all the scenes would have an error in the same direction, so the figures derived can reasonably be considered outside limits.

The uncertainty in storage estimates at spillway elevation (661 ft) caused by classification threshold uncertainty, as computed above, is +15,000 and –16,000 acre-ft.

Masking (#5)

Part of the procedure was masking the upper end of the reservoir to define where the reservoir pool stopped and the flowing water started. This was done by a visual assessment of each Landsat scene. To estimate the effect of uncertainty in this procedure, a reasonable maximum and minimum mask for each scene was created and the surface area and storage capacity values were recomputed using the revised mask.

The uncertainty in storage capacity at spillway elevation caused by uncertainties in masking the upper end of the reservoir was +5,000 and –8,000 acre-ft.

Uncertainty in reservoir elevation readings (#6)

A possible source of uncertainty is in the reservoir elevation readings. Storage capacity is computed by multiplying average surface area (acres) by the difference in elevation between any two of the elevations in the elevation vs. area curve. An error in the elevation reading could mean an error in the elevation difference, and thus in the capacity estimate. The effect is significant only for the elevation of the top of the reservoir, because any overestimate in depth on a lower capacity layer will be approximately balanced by an underestimate in the volume of the layer above it. Only the top layer has no layer above it.

To ascertain the effect of errors in depth readings, the reservoir elevation vs. capacity curve was recomputed adding 0.1 ft to the elevation of the reservoir at the time of the Landsat overpasses. The difference in capacity was minimal (less than 450 acre-ft) for the intermediate elevations, and varied from plus or minus 805 acre-ft for the lowest Landsat reservoir elevation (578.51 ft) to plus or minus 4996 acre-ft for the highest Landsat elevation (665.86 ft). The error at spillway elevation (661 ft, an intermediate elevation) was plus 406 and minus 407 acre-ft.

Uncertainty in area and capacity of lowest levels (#7)

The difference interpolation method of computing the capacity has limitations in the lower elevation ranges because the lowest elevation in the 1993 satellite data was 578.51 ft, 48 ft above empty. For reservoir elevations of 546 ft and under, the difference interpolated estimate of surface area was negative, which is clearly not correct, so these values were manually set to zero. Presumably these area estimates and those for some of the elevations just above this are underestimated. Given that the capacity from the 1985 survey for 546 is 1726 acre-ft, it seems reasonable to assume that the underestimate of capacity is not more than about 2000 acre-ft. This error, because it is associated with the lowest reservoir level, is carried through to the upper levels as well.

Table D1 summarizes the estimated surface area error bars for the elevations of the Landsat passes and for spillway elevation, for each of the sources of uncertainty described above. Sources #6 (depth readings) and #7 (lower levels) do not have area error bars. Table D2 lists the same for storage capacity error bars.

Table D1. Painted Rock Reservoir surface area error bars.

			Area error bars (acres)									
	Reservoir elevation	1993 area from Landsat	#1 Mudflats		#2 Rectification		#3 Wind fetch		#4 Threshold		#4 Masking	
Date	(ft above MSL)	(acres)	upper	lower	upper	lower	upper	lower	upper	lower	upper	lower
4 Dec 93	532.10	0	0	0	0	0	0	0	0	0	0	0
2 Nov 93	578.51	7,779	389	−266	48	−48	31	−31	119	−121	0	0
1 Oct 93	594.65	13,328	305	−191	83	−83	49	−49	106	−103	33	0
30 Aug 93	604.88	17,623	410	−345	109	−109	54	−63	172	−187	60	0
29 Jul 93	612.32	21,455	475	−434	133	−133	80	−80	168	−185	50	0
27 June 93	620.61	25,888	421	−384	161	−161	90	−90	177	−184	0	0
26 May 93	631.06	32,303	644	−503	200	−200	122	−122	186	−203	0	0
10 May 93	637.75	36,485	365	−206	226	−226	130	−131	150	−164	225	−200
24 Apr 93	644.22	40,934	346	−270	254	−254	101	−132	165	−179	0	−330
8 Apr 93	651.68	45,795	171	−117	284	−284	152	−152	142	−156	207	−245
31 Mar 93	655.24	48,633	311	−149	302	−302	157	−157	187	−191	0	−447
7 Mar 93	665.86	55,141	108	−58	342	−342	177	−177	197	−241	689	0

Table D2. Painted Rock Reservoir storage capacity error bars.

			Capacity error bars (acre-ft)					
	Reservoir elevation	*1993 area capacity*	*#1 Mudflats*		*#2 Rectification*		*#3 Wind fetch*	
Date	*(ft above MSL)*	*(acre-ft)*	*upper*	*lower*	*upper*	*lower*	*upper*	*lower*
2 Nov 93	578.51	99,843	8,275	–5,670	1,027	–1,027	652	–651
1 Oct 93	594.65	269,280	13,873	–9,363	2,083	–2,083	1,296	–1,294
30 Aug 93	604.88	427,929	17,529	–12,104	3,064	–3,064	1,823	–1,865
29 Jul 93	612.32	573,090	20,820	–15,000	3,966	–3,966	2,323	–2,396
27 June 93	620.61	769,297	24,533	–18,389	5,182	–5,182	3,027	–3,100
26 May 93	631.06	1,072,738	30,097	–23,024	7,067	–7,067	4,134	–4,208
10 May 93	637.75	1,302,822	33,470	–25,396	8,494	–8,494	4,978	–5,053
24 Apr 93	644.22	1,553,409	35,770	–26,936	10,047	–10,047	5,728	–5,904
8 Apr 93	651.68	1,876,677	37,699	–28,378	12,052	–12,052	6,672	–6,964
31 Mar 93	655.24	2,044,759	38,557	–28,851	13,094	–13,094	7,221	–7,514
7 Mar 93	665.86	2,595,400	40,783	–29,950	16,511	–16,511	8,993	–9,291
Spillway	661	2,334,804	40,032	–29,566	14,894	–14,894	8,155	–8,451

		Capacity error bars (acre-ft)							
	Reservoir elevation	*#4 Threshold*		*#5 Masking*		*#6 Depth reading*		*#7 Lowest levels*	
Date	*(ft above MSL)*	*upper*	*lower*	*upper*	*lower*	*upper*	*lower*	*upper*	*lower*
2 Nov 93	578.51	2,528	–2,584	0	0	805	–805	2,000	0
1 Oct 93	594.65	4,345	–4,395	267	0	1,443	–1,443	2,000	0
30 Aug 93	604.88	5,770	–5,880	744	0	1,815	–1,815	2,000	0
29 Jul 93	612.32	7,035	–7,263	1,153	0	2,157	–2,157	2,000	0
27 June 93	620.61	8,462	–8,789	1,360	0	2,536	–2,536	2,000	0
26 May 93	631.06	10,356	–10,807	1,360	0	3,042	–3,042	2,000	0
10 May 93	637.75	11,481	–12,035	2,113	–670	3,394	–3,394	2,000	0
24 Apr 93	644.22	12,498	–13,144	2,841	–2,385	3,793	–3,793	2,000	0
8 Apr 93	651.68	13,640	–14,394	3,612	–4,528	4,159	–4,159	2,000	0
31 Mar 93	655.24	14,224	–15,012	3,981	–5,759	4,347	–4,347	2,000	0
7 Mar 93	665.86	16,262	–17,304	7,639	–8,131	4,995	–4,995	2,000	0
Spillway	661.00	15,315	–16,190	5,057	–7,635	406	–407	2,000	0

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13. ABSTRACT (*Maximum 200 words*)

The Painted Rock Reservoir, southwest of Phoenix, Arizona, had a storage capacity of about 2.5 million acre-ft in 1959, when dam closure was made. It was projected that the reservoir would lose about 200,000 acre-ft of its capacity to sedimentation over 50 years. When the flood of record occurred in 1993, however, it was feared that as much as 500,000 acre-ft of capacity had been lost, and an updated capacity estimate was needed. Because a proposed conventional reservoir survey turned out to be prohibitively expensive, it was decided to investigate the use of Landsat Thematic Mapper remotely sensed data, acquired at multiple reservoir levels, to obtain an updated capacity estimate at a more reasonable cost.

Nineteen Landsat Thematic Mapper scenes from 1993 and 1995 were obtained, including reservoir elevations ranging from empty to 5 ft above spillway elevation. Water surface area was determined for each Landsat scene using computer classification of the digital imagery. These surface area values, together with reservoir elevation records for the time of the Landsat data acquisitions and 1985 survey information, were used to generate an updated elevation vs. surface area curve for the reservoir, which in turn was used to compute an updated elevation vs. storage capacity curve. Investigation results indicate that the Painted Rock Reservoir lost approximately 157,000 acre-ft of storage capacity to sedimentation between 1953 and 1993, significantly less than the 500,000 acre-ft previously feared lost.

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This technique of using remotely sensed data to update area and capacity curves could be applied to other reservoirs, if (among other conditions) there is a record of reservoir elevation at the time of acquisition of the remotely sensed data, and if cloud-free data are available for the entire range of reservoir elevations from full to empty.